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Conceptual Model to Support PCB Management and Monitoring in the Emeryville Crescent Priority Margin Unit

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Preface

The goal of RMP PCB special studies over the next few years is to inform the review and possible revision of the PCB TMDL and the reissuance of the Municipal Regional Permit for Stormwater, both of which are tentatively scheduled to occur in 2020. Conceptual model development for a set of four representative priority margin units will provide a foundation for establishing an effective and efficient monitoring plan to track responses to load reductions, and will also help guide planning of management actions. The Emeryville Crescent was the first PMU to be studied in 2015-2016, and is the subject of this report. The San Leandro Bay PMU is second (2016-2017), Steinberger Slough in San Carlos is third (2017), and Richmond Harbor will be fourth (2018).

The conceptual model reports for these four PMUs will be developed and presented using a consistent framework, and will build on each other to form an integrated assessment of these four areas. The lessons learned from these analyses will also be more generally applicable to similar contaminated sites on the margins of the Bay.

Acknowledgements

This report was improved by written and oral comments on draft materials from Jan O'Hara, Richard Looker, Arleen Feng, Andy Jahn, Frank Gobas, Craig Jones, Mike Connor, Tom Mumley, and Luisa Valiela.

Table of Contents

Executive Summary

The 2014 update of the RMP PCB Strategy called for a multi-year effort to implement the recommendations of the PCB Synthesis Report (Davis et al. 2014) pertaining to:

1. identifying margin units that are high priorities for management and monitoring,
2. development of conceptual models and mass budgets for margin units downstream of watersheds where management actions will occur, and
3. monitoring in these units as a performance measure.

The goal of the effort is to inform the review and possible revision of the PCB TMDL and the reissuance of the Municipal Regional Permit for Stormwater (MRP), both of which are tentatively scheduled to occur in 2020. Conceptual model development for four priority margin units (PMUs) that are high priorities for management and monitoring will provide a foundation for establishing effective and efficient monitoring plans to track responses to load reductions and will also help guide planning of management actions. The Emeryville Crescent (the Crescent) is the subject of this report and the first PMU to be studied.

The goal of this report is to answer three questions related to management and monitoring of PCBs in priority margin units.

1. Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?
2. How should tributary loads be managed to maximize PMU recovery?
3. How should the Crescent be monitored to detect the expected reduction?

This report provides a technical foundation for answering these questions to the extent possible with existing information, and identifies the information that is most urgently needed to provide answers that are sufficient to support decision-making.

A conceptual model was developed that includes four major elements:

1. loading from the watersheds;
2. initial deposition and retention;
3. processes determining the long-term fate of PCBs in sediment and water; and
4. bioaccumulation in the food web.

This conceptual model provided a basis for the following answers to the three questions posed above.

1) Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?

A simple, one-box fate model suggests that a 15 cm mixed sediment layer could respond fairly quickly to significant changes in tributary inputs, with a change to a mixed layer concentration approaching a long-term steady state (and a new mass balance of inputs and losses) in 10 years. However, this rate of change to steady state is likely somewhat accelerated by the one-box assumption, and highly dependent on assumptions and estimates made for the input parameters. Nonetheless, the simple fate model is useful for illustrating the interactions among the numerous environmental processes affecting PCB fate and the likely net direction and relative rate of change under different scenarios.

These predicted changes in the mixed layer concentration would lead to similar changes in PCB exposure broadly across the entire food web. A significant amount of food web transfer of PCBs to species of interest occurs through benthos that are surface deposit feeders and filter feeders that can be expected to respond relatively quickly to reductions in ambient surface concentrations, which may in turn respond relatively quickly to reductions in tributary inputs.

2) How should tributary loads be managed to maximize PMU recovery?

The Ettie Street Pump Station (ESPS) Watershed accounts for a minimum estimated 41% of the tributary export of PCBs into the Crescent. The load estimate for the Temescal Creek watershed also accounts for 41%, and 18% is estimated to come from the Emeryville Crescent North watershed. However, per unit area of each watershed, ESPS Watershed has the highest yield (19 g/km^2), followed by the Emeryville Crescent North Watershed (10 g/km^2) and the Temescal Creek Watershed (8.3 g/km^2). Recovery of the Crescent from PCB contamination would be maximized by pursuing a load reduction strategy that encompasses any remaining older industrial areas in all three of these watersheds. However, given the greater density of sources and source areas indicated by the yields, the most cost-effective phased strategy would be to focus earlier efforts in the ESPS Watershed.

The vast majority of the tributary loads that are retained within the Crescent are likely delivered by storms with magnitudes less than the 1:1 year return interval. More flow is delivered by these smaller storms, and more of the input is likely to be retained. From a PMU perspective, it appears that managing and monitoring these smaller storms is more important than managing and monitoring loads from larger storms. However, given the uncertainty in the temporal distribution of the loads, further data collection would be needed to verify that this conclusion is not an artifact of limited data and the assumption that rainfall distribution is a good surrogate for temporal load distribution.

3) How should we monitor to detect the expected reduction?

Preliminary field studies are needed to confirm the hypotheses put forward and information gaps identified in this conceptual model report. These include the following.

1. A survey of the presence, distribution, and PCB burdens of biota in the Crescent. Measurement of PCB concentrations in the two prey fish species is needed to establish a baseline. Sampling for shiner surfperch should also be

attempted to determine the distribution of this species in the Crescent and evaluate PCB concentrations where it is present.

2. A survey of the spatial pattern of PCB concentrations in surface and subsurface sediment.
3. Other data (in addition to sediment concentrations) needed to quantify routes of exposure in prey fish, including data on prey fish diet (i.e., gut contents) and water column PCB concentrations. In other words, data needed to incorporate prey fish into the PCB food web model (Gobas and Arnot 2010) should be collected.
4. Data on PCB loads in stormwater from Emeryville Crescent North and Temescal Creek or data on concentrations sufficient to calibrate a model used to estimate loads.

Monitoring for tracking declines in PCB loads and impairment of the Crescent should include the following elements.

1. Annual monitoring of concentrations in prey fish. After an initial period that characterizes interannual variation and baseline concentrations, a power analysis could be conducted to determine the appropriate monitoring effort needed to observe a desired degree of change.
2. Periodic monitoring of concentrations in shiner surfperch as an ongoing measure of impairment. After an initial survey, this could perhaps be done on a five-year cycle as part of RMP sport fish monitoring.
3. Tributary concentration and possibly load monitoring that is consistent with the trend monitoring strategy under development by the Sources, Pathways, and Loadings Workgroup, ideally spatially and temporally linked to any ongoing fish and sediment monitoring in the Crescent.
4. Periodic (preferably annual) extreme near field receiving water sediment traps or surface sediment monitoring to approximately capture whole season net load concentrations. This in combination with annual prey fish monitoring would illustrate any lags or inertial responses between loading changes and total inventory or food web effects.

1. Introduction

The RMP PCB Strategy Team formulated a PCB Strategy in 2009. The Team recognized that a wealth of new information had been generated since the PCBs TMDL Staff Report (SFBRWQCB 2008) was prepared. The Strategy articulated management questions to guide a long-term program of studies to support reduction of PCB impairment in the Bay. The PCB Team recommended two studies to begin addressing these questions. The first recommended study was to take advantage of an opportunity to piggyback on the final year of the three-year prey fish mercury sampling in 2010 to collect data on PCBs in prey fish also. The second study that was recommended was a synthesis and conceptual model update based on the information that had been generated since the writing of the TMDL Staff Report.

The prey fish monitoring revealed extremely high concentrations of PCBs in the food web in several areas on the Bay margins (Greenfield and Allen 2013), and highlighted a need to develop a more detailed conceptual model than the one-box model used as a basis for the TMDL. A model that would support the implementation of actions to reduce loads from small tributaries, a primary focus of the TMDL, would be of particular value. A revised conceptual model was developed that shifted focus from the open Bay to the contaminated areas on the margins where impairment is greatest, where load reductions are being pursued, and where reductions in impairment in response to load reductions would be most apparent (Davis et al. 2014).

The margins appear to be a collection of distinct local food webs that share some general similarities but are largely functionally discrete from each other. Monitoring, forecasting, and management should therefore treat these margin locations as discrete local-scale units. Local-scale actions within a margin unit, or in upstream watersheds, will likely be needed to reduce exposure within that unit. Better characterization of impairment on the margins through more thorough sampling of sediment and biota would help focus attention on the margin units where the need for action is greatest ("priority margin units" or PMUs), and will also provide an important performance measure for load reduction actions taken in local watersheds. Davis et al. (2014) recommended a focus on assessing the effectiveness of small tributary load reduction actions in priority margin units, and provided an initial foundation for these activities.

The 2014 update of the PCB Strategy called for a multi-year effort to implement the recommendations of the PCB Synthesis Report (Davis et al. 2014) pertaining to:

1. identifying margin units that are high priorities for management and monitoring,
2. development of conceptual models and mass budgets for margin units downstream of watersheds where management actions will occur, and
3. monitoring in these units as a performance measure.

A thorough and thoughtful planning effort is warranted given the large expenditures of funding and effort that will be needed to implement management actions to reduce PCB loads from urban stormwater.

The goal of RMP PCB Strategy work over the next few years is to inform the review and possible revision of the PCB TMDL and the reissuance of the Municipal Regional Permit for Stormwater (MRP), both of which are tentatively scheduled to occur in 2020. Gilbreath et al. (2015) identified four margin units that are high priorities for management and monitoring. Conceptual model development for these four priority margin units will provide a foundation for establishing an effective and efficient monitoring plan to track responses to load reductions and also help guide planning of management actions. The Emeryville Crescent (Figure 1-1) is the subject of this report and the first PMU to be studied.

The goal of this report is to answer the following three questions related to management and monitoring of PCBs in priority margin units.

1. Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?
2. How should tributary loads be managed to maximize PMU recovery?
3. How should the Emeryville Crescent PMU (the Crescent) be monitored to detect the expected reduction?

This report is intended to provide a technical foundation for answering these questions to the extent possible with existing information, and to identify the information that is most urgently needed to provide answers that are sufficient to support decision-making. The report is therefore intended for a technical audience.

The report includes four sections describing the major elements of the conceptual model for PCBs in the Crescent (Figure 1-2):

- Section 2: loading from the watersheds;
- Section 3: initial deposition and retention;
- Section 4: processes determining the long-term fate of PCBs in sediment and water; and
- Section 5: bioaccumulation in the food web.

The last section (Section 6) presents answers to the management questions.

Figure 1-1. The Emeryville Crescent at low tide. Marsh, intertidal mudflat, and subtidal areas are visible.

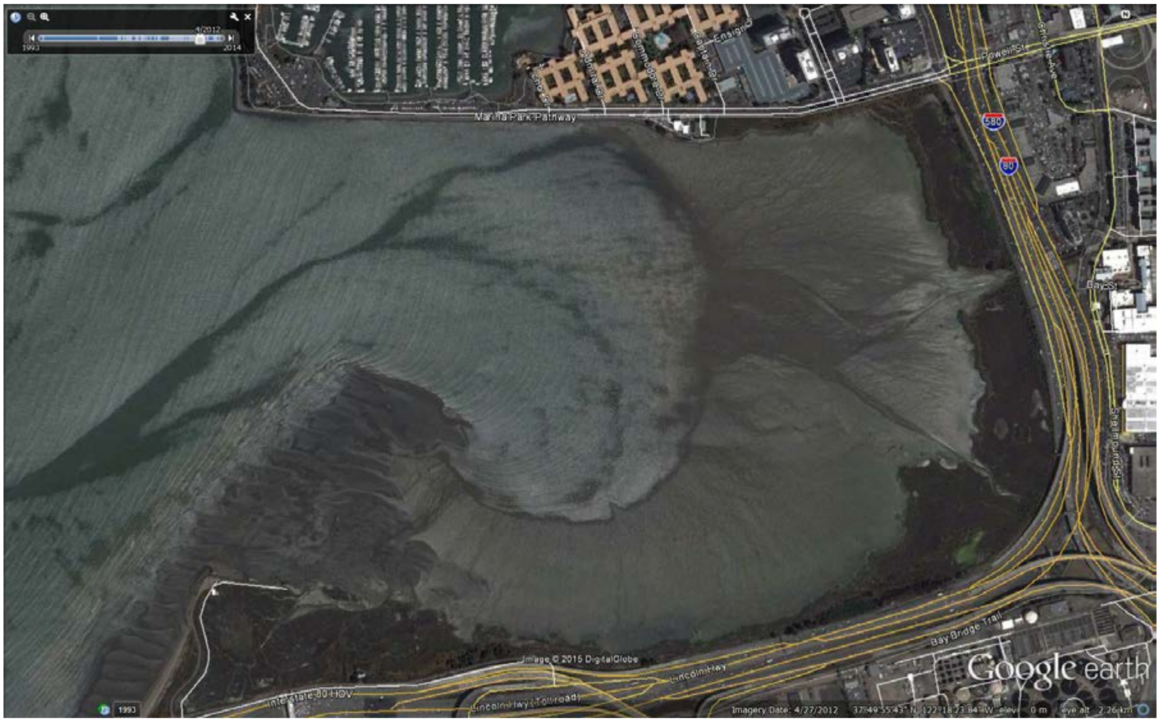
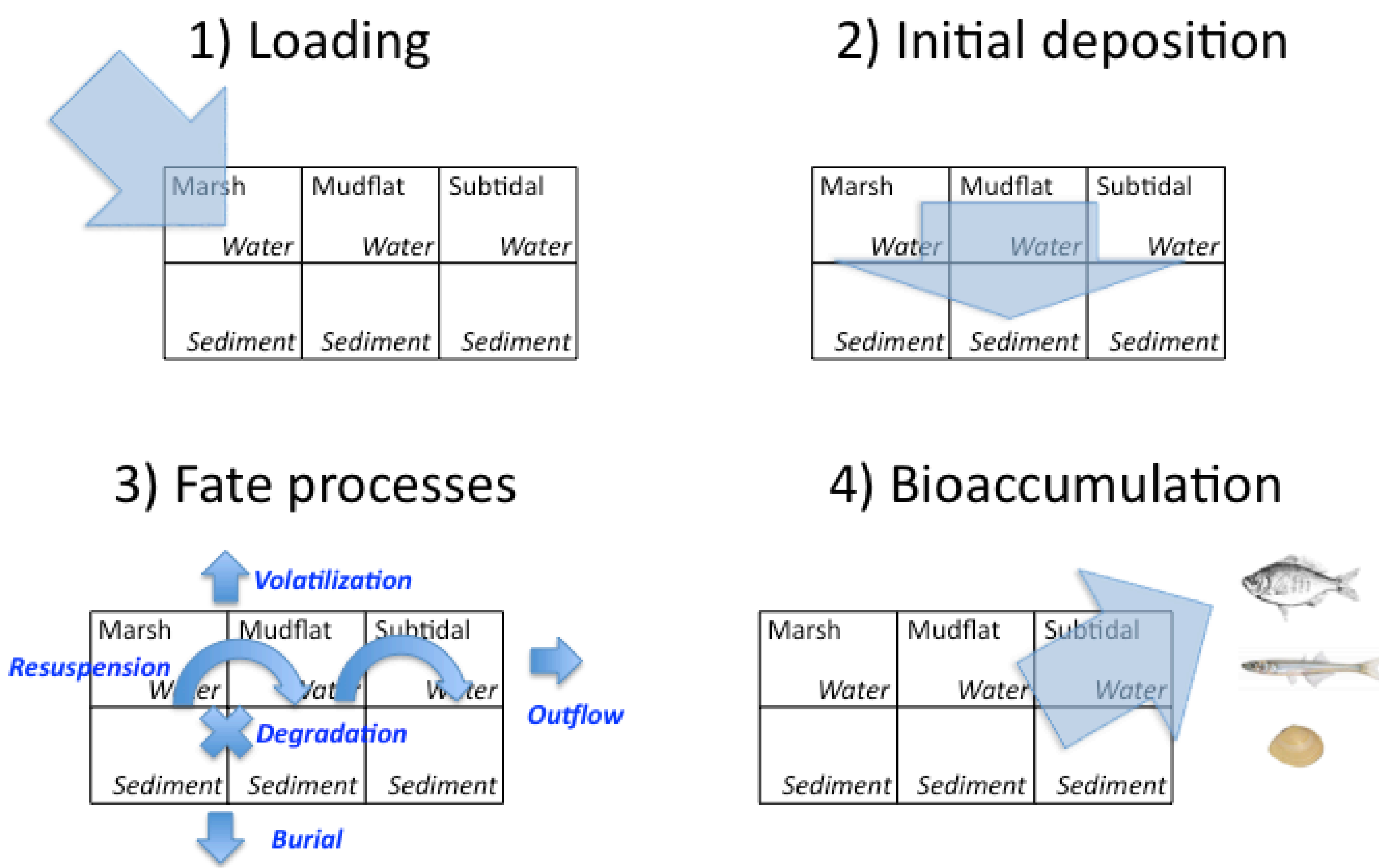


Figure 1-2. Overall conceptual model.



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2. Tributary Loading

a. Tributary Watersheds: General Profiles

The watershed draining to Emeryville Crescent ("the Crescent") covers an area of 37.8 km^2 of mixed land use (Figures 2-1 and 2-2). Although a portion of the watershed consists of open space in the form of urban parks and some upland areas, the most predominant land use is a mix of mostly medium to high density residential, commercial, and transportation. Although historically the area close to the Bay margin was more predominantly industrial, today, with the onset of redevelopment in the last several decades, the area associated with older industrial land uses is small and continuing to diminish. Drainage into the Crescent is dominated by urban runoff entering at two locations (Figure 2-1).

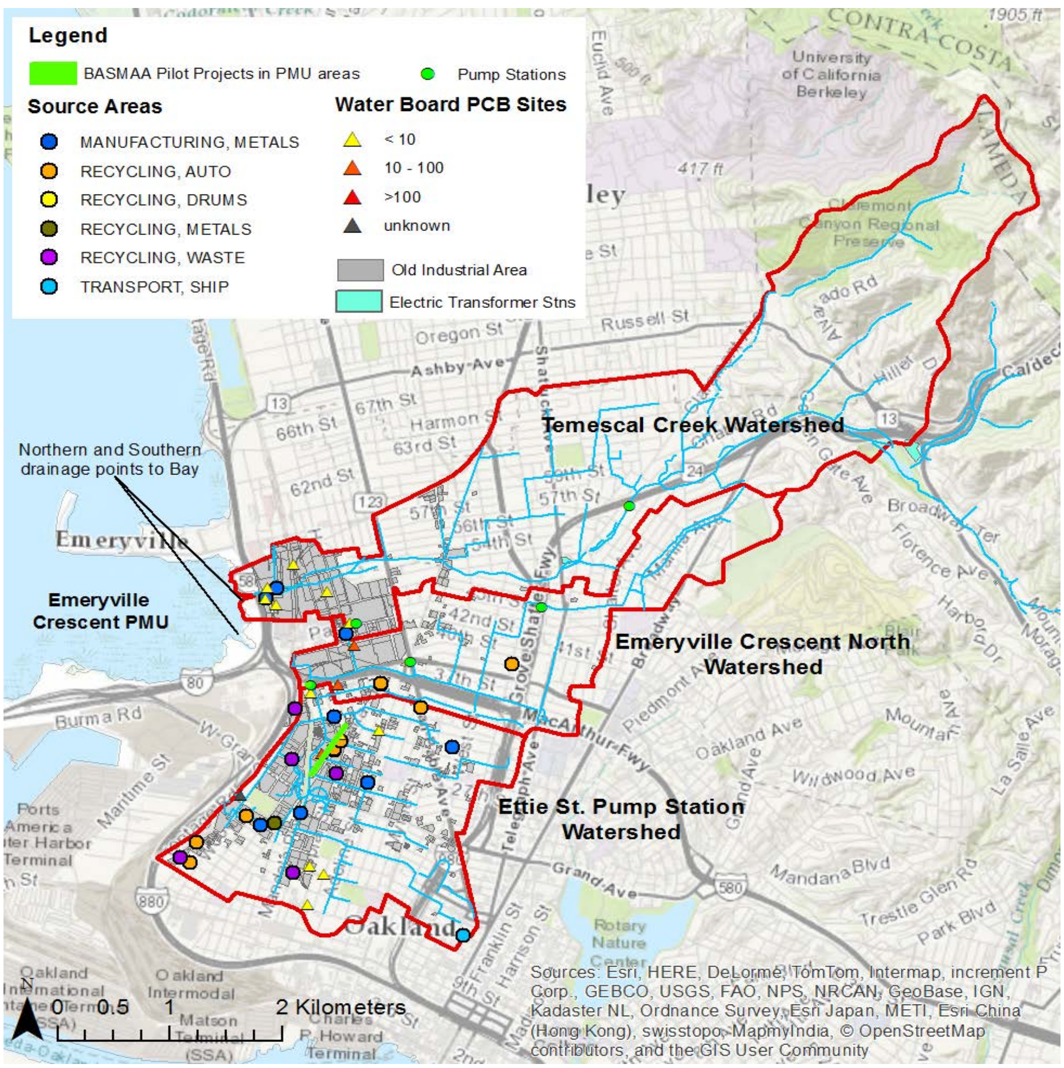

Figure 2-1. Main tributary watersheds of the Emeryville Crescent PMU.

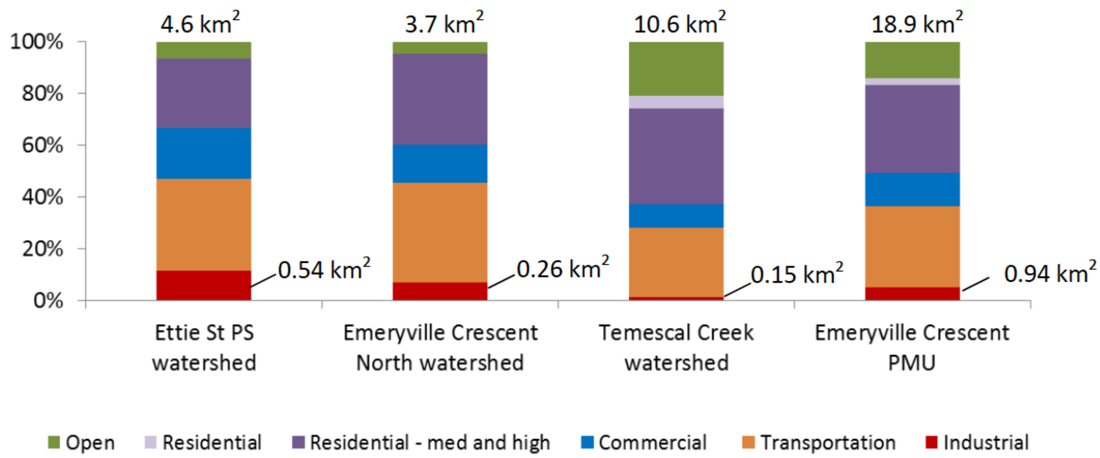

Figure 2-2. Land use in the Emeryville Crescent PMU watersheds (ABAG 2005). Note that this land use dataset represents land use during approximately 2002, and therefore is 15 years old. Portions of these watersheds have undergone redevelopment since 2002.

The southern pour point drains a total area of 8.3 km^2 and comprises two subwatersheds – Ettie Street Pump Station (ESPS) Watershed and Emeryville Crescent North Watershed – which come together approximately 0.6 km upstream from the Bay shoreline. ESPS Watershed (4.6 km^2) is situated between major Oakland highways (580, 880, and 980), and drains the majority of the neighborhood called West Oakland. Located in close proximity to the Port of Oakland and numerous rail lines and spurs, the ESPS Watershed is a highly impervious (76%), old urban landscape with a relatively high percentage of older industrial area (10%). West Oakland embodies a rich cultural history, and although the industrial history has been in slow decline for approximately 80 years, revitalization of the neighborhood has begun in the form of new affordable housing, transit-oriented housing and businesses, and other forms of redevelopment which are likely to continue.

The Emeryville Crescent North Watershed (3.7 km^2) is situated between ESPS and Temescal Creek watersheds and comprises the southern portions of Emeryville, North Oakland, and Rockridge neighborhoods. The land use profile of Emeryville Crescent North Watershed is very similar to that of ESPS Watershed, but includes only about half the amount of industrial area and less commercial area in exchange for more residential. The Emeryville portion of the watershed, once a more industrial area, is now dominated by commercial big box stores (Note: some of this redevelopment occurred after 2002 and therefore the percentage of industrial area is over-represented while commercial area is under-represented).. North Oakland is predominantly residential but includes the major BART connector station, MacArthur BART, and Highway 24, and is currently experiencing revitalization and gentrification. The Rockridge neighborhood is residential with some commercial area.

Temescal Creek Watershed drains 10.6 km^2 below Lake Temescal and enters the Crescent from the northern drainage point. The upper watershed of Temescal Creek consists of the Claremont Hills, and then runs through Claremont, South Berkeley, North Oakland, and a large portion of Emeryville. Claremont, South Berkeley, North Oakland, and the eastern portions of Emeryville are predominantly residential areas with some commercial, while the west Emeryville area includes the large commercial center of Bay Street, as well as a large proportion of commercial-industrial buildings including Pixar (Note: some of this redevelopment occurred after 2002 and therefore the percentage of industrial area is over-represented while commercial area is under-represented). A short section of the 80/580 freeway, along with a 4 km stretch of Highway 24 and 2 km stretch of Highway 13, all pass through Temescal Creek Watershed below Lake Temescal.

b. Current PCB Export to the PMU

PCB loads from ESPS Watershed have been previously estimated in two efforts including 1) an EBMUD Environmental Enhancement Project and Supplemental Environmental Project (EBMUD 2010) and 2) the RMP WY 2011 watershed reconnaissance study (McKee et al. 2012). The EBMUD effort was focused on characterizing stormwater, dry weather, and first flush flows for investigating the potential impacts of diversion from the Pump Station to nearby EBMUD facilities for treatment. Sampling occurred between 2008 and 2010. EBMUD collected 10 discrete grab samples in 10 storm events, five discrete grab samples in five first flush events, and nine discrete grab samples during eight events in dry weather. PCB loads were estimated by multiplying the average dry (4.6 ng/L), wet (50.5 ng/L), and first flush (36.8 ng/L) concentrations by the estimated dry (0.52 MGD), wet (14.1 MGD), and first flush (9.5 MGD) flows and the number of days in each category (300, 60 and 5, respectively). Applying this method yielded an average annual discharge of 4.0 Mm^3 and PCB load of 171 g.

The RMP WY 2011 reconnaissance effort included sampling the ESPS during one storm event and collecting 4 discrete grab samples during the course of the storm. PCB loads for ESPS Watershed were then estimated by using an SSC-weighted mean[1] concentration of PCBs (60.4 ng/L) applied to the climatically-adjusted average annual discharge volume (5.7 Mm^3) using empirical flow data from the Pump Station for the period 5/2005 - 9/2008. Applying this method yielded an average annual PCB load for ESPS of 343 g.

[1] In the absence of flow to weight the estimates of event mean concentration (EMC) towards representative high flow conditions when the majority of load is transported, we assumed that SSC would be a reasonable surrogate for flow given the typical strong relationship between SSC and flow. Thus we used SSC as a means for weighting the concentrations to estimate the event mean concentration for use in the loads calculations.

We subsequently re-evaluated the empirical flow data at ESPS and discovered that discharge had been overestimated by 3- to 4-fold. Thus, we conclude that the previous loading estimates made by EBMUD (2010) and McKee et al. (2012) were likely in error and biased high by a factor of around 4-fold. Previous estimates of Pump Station flows for both studies relied on the station's SCADA system logs of pump run times in combination with the nominal capacity of each pump. This method did not include the use of a continuous stage record, which is important since the pump efficiency (or rate at which the water is pumped) decreases as the head above the pump decreases. Without this stage record, the flow was overestimated since the full pump capacity was applied to the entire time interval that the pump log indicated the pumps were on. Stage is currently not recorded at the pump station. Although SFEI is investigating ways to estimate the flow using just the pump log, at this time, we must reject the ESPS empirical flow record. To more accurately measure flows, we recommend using an instrumentation set-up as was done by the RMP during WYs 2013-2014 at the North Richmond PS (Gilbreath et al. 2016). This setup included continuous wet well stage measurement using a pressure transducer and measurement of the pump RPMs using optical proximity sensors. These data, combined with the station pump curve provided by the pump station manager, allowed for relatively accurate calculation of discharge.

In lieu of empirical flow data, ESPS flows were estimated using the Regional Watershed Spreadsheet Model (RWSM; Wu et al. 2016). The RWSM applies regionally calibrated coefficients for runoff based on a combination of land use, slope, and soil type. Average annual flow volumes of 1.5 Mm^3 are estimated using the RWSM, equivalent to a runoff coefficient of about 0.6 (or 60% of mean annual rainfall). No flow data exist for either the Emeryville Crescent North or Temescal Creek watersheds, and therefore flows were estimated for these watersheds also using the RWSM.

To estimate average annual PCB loads for ESPS Watershed, flows generated from the RWSM were applied to the SSC-weighted mean concentration of the EBMUD wet weather influent samples and the RMP WY 2011 stormwater grab samples (58.8 ng/L). For Emeryville Crescent North and Temescal Creek watersheds, where no empirical PCB concentrations have been measured, loads were estimated using RWSM-estimated flows and the latest version of the RWSM PCB calibration coefficients (Wu et al. 2017). The resulting revised loads estimates (Table 2-1) include a much smaller mass for the ESPS Watershed (87 g/yr). The estimated range for the entire PMU is 141 – 369 g/year, with a best estimate of 214 g/year. Although for planning purposes these loads are conceptually reasonable, the main data weaknesses at this time include the following.

- Empirical flow data are lacking for all of these watersheds
- Concentration data of any kind are lacking for Emeryville Crescent North and Temescal Creek watersheds.

- Flow and concentration data collected in the manner that allow for either calibration of the model or empirical-based loads computations are lacking.
- The underlying land use data that do not accurately account for areas redeveloped since around 2000. A large percentage of area categorized as old industrial has been redeveloped, particularly in the lower portion of Temescal Creek Watershed. By accounting for these changes, we acknowledge the current load estimate for Temescal Creek Watershed is likely biased high, perhaps by approximately 30-40%. An updated land use dataset would be of great value for regional modeling purposes.

Table 2-1. Average annual load estimates for the Emeryville Crescent Margin Unit watersheds using RWSM.

Watershed	Total Area (km^2)	Total Runoff Volume (Mm^3)	PCBs Load - Low Estimate (g)	PCBs Load - High Estimate (g)	PCBs Load - Best Estimate (g)	PCBs Yield - Best Estimate ($\mu g/m^2$)	Method
Emeryville Crescent North WS	3.7	1.2	24	81	39	10.5	RWSM flows and RWSM estimated PCB concentrations
ESPS WS	4.6	1.5	61	113	87	18.9	RWSM flows and empirical PCB concentrations
Temescal Creek WS	10.6	3.3	56	175	88	8.3	RWSM flows and RWSM estimated PCB concentrations
Total for Margin Unit	18.9	6.0	141	369	214	11.3	

c. Temporal Dynamics of Loading into the PMU

To better understand how the flow of storm water, suspended sediment, and PCBs interact with or flush through the Crescent, estimates of annual averages were derived for loads delivered by the following flow types:

i. summer and winter non-storm flow;
ii. an “average” storm;
iii. a 1:1 year return interval storm;

iv. a 1:5 year return interval storm; and
v. a 1:10 year return interval storm.

This was accomplished using, as a surrogate, loads delivered for different types of storm events from three watersheds in the region for which we have multiple years of continuous loads estimates, and which are similar in land use characteristics to the Crescent (see Appendix 1 for method details). The low and high estimates for the three reference stations were used to produce the low and high range of load transport for each storm category in the Crescent watersheds (Tables 2-2, 2-3 and 2-4).

Table 2-2. PCB loads transported annually and for select storm categories (load as a percentage of the average annual load) in reference watersheds.

	Area (km^2)	Long Term (40 year) Avg Annual Load (g)	Long Term (40 year) Avg Annual Yield (g/km^2)	Summer and winter non-storm flow PCB load	% of load in avg storm	% of load in 1:1 yr storm	% of load in 1:5 yr storm	% of load in 1:10 yr storm
Sunnyvale East Ch	15.19	134	9.4	NA	0.4%	4.7%	9.5%	11.6%
Z4LA	4.17	14.6	3.5	5%	1.8%	5.2%	10.1%	12.2%
N Richmond PS	1.96	11.4	5.8	7%	1.7%	4.6%	9.6%	11.8%

Table 2-3. Range for three reference watersheds of the percentage load (relative to the average annual PCB load) transported for selected storm recurrence intervals.

	Low	High
% of load in avg storm	0.4%	1.8%
% of load in 1:1 yr storm	4.6%	5.2%
% of load in 1:5 yr storm	9.5%	10.1%
% of load in 1:10 yr storm	11.6%	12.2%

Table 2-4. PCB load estimates for different storm categories in the Crescent watersheds.

	Long-Term (40 year) Avg Annual Load (g)	Long-Term (40 year) Avg Annual Yield (g/km2)	Summer and winter non-storm flow PCB load (g)	Avg storm load estimate (g)		Load in 1:1 yr storm (g)		Load in 1:5 yr storm (g)		Load in 1:10 yr storm (g)	
				Low	High	Low	High	Low	High	Low	High
ESPS WS	87	18.9	5.2	0.3	1.6	4.0	4.5	8.3	8.8	10.1	10.6
Temescal Creek WS	88	8.3	5.3	0.4	1.6	4.0	4.6	8.4	8.9	10.2	10.7
Emeryville Crescent North WS	39	10.5	2.3	0.2	0.7	1.8	2.0	3.7	3.9	4.5	4.8
Total for Margin Unit	214	37.8	12.8	0.9	3.9	9.8	11.1	20.3	21.6	24.8	26.1

To support mass budget calculations for the Crescent that include conservation of total load mass over a year or multiple years, we estimated a long-term, continuous dataset of daily PCB loads for the Crescent (see Appendix 1 for method details). The exceedance frequency curve for estimated daily PCB loads and a summary of load exceedances are shown in Figure 2-3 and Table 2-5.

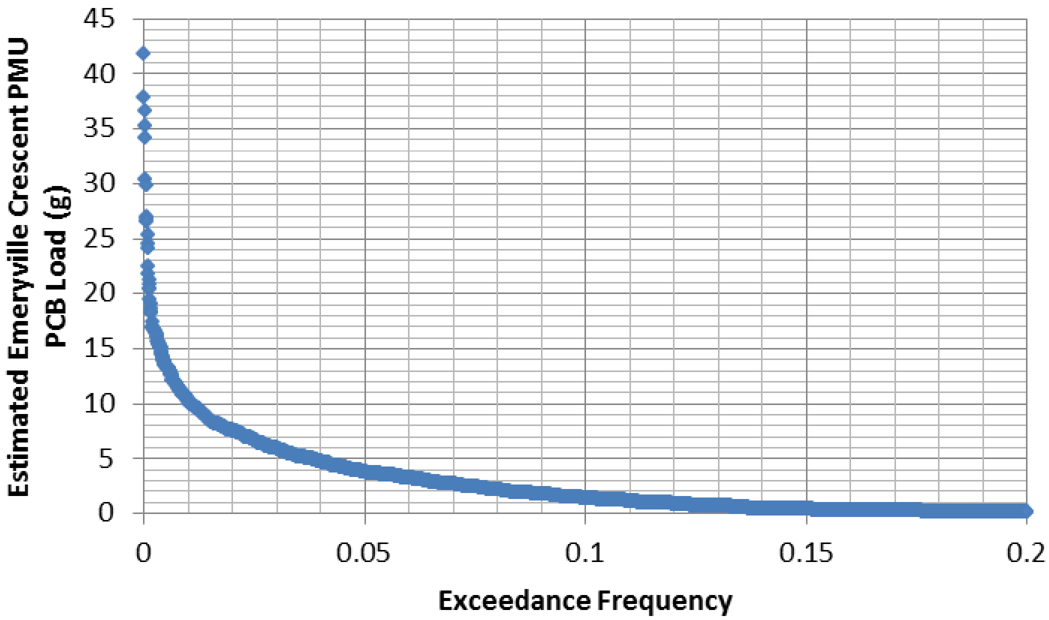

Figure 2-3. Exceedance frequency of estimated daily Crescent PCB loads over a 40-year time period (WY 1971 – 2010).

Table 2-5. Summary of load exceedances in the ESPS Watershed and combined Crescent watersheds.

	ESPS Watershed only	Emeryville Crescent PMU
Avg Annual Load (g)	87	214
Mean Daily Load (g)	0.24	0.59
Load (g) Exceeded 1 % of time	4.1	10.1
Load (g) Exceeded 2 % of time	3.0	7.5
Load (g) Exceeded 5% of time	1.5	3.7
Load (g) Exceeded 10 % of time	0.5	1.2
Load (g) Exceeded 20 % of time	0.017	0.043

A comparison was made between the loads estimate methods (the "recurrence interval method" generated by finding the percentage of load transported during specific storm types at reference watersheds, and the "continuous loads method" generated by using a long-term, continuous rainfall record) to ensure that the results generally corroborate one another. The two methods produce similar results (Table 2-6), although the recurrence interval method results suggest less load transport during these larger storm types than does the continuous loads method. A better estimate of return frequency of loads or the distribution of loads over time relative to climatic variation could be obtained with empirical observations of PCB concentrations in the watershed during winter storms over a number of years or by gathering enough observations in the Crescent watersheds to calibrate a dynamic simulation model such as the Stormwater Management Model (SWMM).

Although storm events larger than the 1:1 year event can transport a significant portion of the PCB load for any given year, events of that size occur infrequently. By identifying the 1:1 year event in the long-term continuous loads dataset, it is possible to estimate the percentage of long term PCB load delivered to the Crescent during the dry season and more frequent smaller storm events versus less frequent but larger events. Based on the continuous loads method, it is estimated that 92% of the long-term PCB load to the Crescent is transported during the dry season and storm events smaller than the 1:1 storm (Table 2-6).

Table 2-6. Summary comparison of the two methods for estimating loads in the Crescent watersheds.

Recurrence Event	% of average annual load transported - Recurrence Interval method	% of average annual load transported - Continuous loads method	% of long-term load transported during storms smaller than the Recurrence Event - based on Continuous loads method
1:1 year event	4-5 %	8%	92%
1:5 year event	9-10 %	14%	97%
1:10 year event	11-12 %	16%	98%

d. Partitioning of PCB Exports from the Watersheds

Little is known in the San Francisco Bay region about the proportion of PCBs on varying grain size fractions. To our knowledge, the only estimates of PCB partitioning in the region were made by Yee and McKee (2010), who carried out a settling experiment to estimate the portion of PCB loads that were in different size fractions. There have also been data collected more recently by BASMAA through the Clean Watersheds for a Clean Bay (CW4CB) project that may also be helpful when they are made available. The outcome of this simple apportionment exercise is to make some first order estimates for PCBs in each of three size fractions: <0.25 µm, 25-75 µm, and >75 µm.

The limited data available (Table 2-7, data from Yee and McKee [2010]) suggest that the percentage of PCB mass in different grain size fractions can vary widely, especially for the smallest fraction (<25 um). We recommend using the minimum and maximum of the results available as an estimate of the range of PCB mass in different grain sizes, and the average as the best estimate.

Table 2-7. The fraction of PCB mass in different grain size fractions. From Yee and McKee (2010).

Sample/site	PCB (ng/L)	%<25um incl. dissolved	%25-75 um	%>75 um
Z4-201	17	73	13	14
Z4-203	30	49	23	28
Z4-204	23	46	21	33
Z4-205	29	38	31	31
RS-1003	38	28	26	46
RS-1004	17	51	16	33
Range	17 - 38	28 - 73 %	13 - 31%	14 - 46%
Average	26	48%	22%	31%

PCBs in the Dissolved Fraction

In the absence of any data for the PMU watersheds or other Bay Area small urban tributaries, the dissolved proportion of PCBs was evaluated in a literature review and by manipulating the PCB and SSC data from other Bay Area tributaries. The literature review supported that PCBs have a high affinity for sorption to suspended sediment and organic matter in stormwater runoff, and lower suspended particulate concentrations tend to persist during periods of dry weather, so dry weather conditions would favor greater proportional transport of dissolved phase PCBs. When data from empirical studies in the literature review are stratified between dry and wet weather conditions, the data points representing dry weather sample collection have higher overall proportions of dissolved PCBs (Figure 2-4, 52-93% versus 10-52% for wet weather sampling).

Samples collected from the water column and bed sediment of contaminated tributaries and storm drains of Bay Area watersheds typically have PCB congener patterns indicative of high-molecular weight Aroclors 1254 and 1260 (KLI 2001, Johnson et al., 2000, Leatherbarrow et al., 2002), and therefore are expected to be primarily associated with suspended sediment transported during storm events. ESPS samples collected from the water column in WY 2011 (McKee et al. 2012) were also dominated by congeners indicative of Aroclors 1254 and 1260, however the ESPS samples were composed of greater proportions of the Aroclor 1242 and 1248 congeners than most other watersheds in the study, suggesting that a larger portion of the total PCBs may be in the operationally defined dissolved phase than is otherwise typical for the Bay Area.

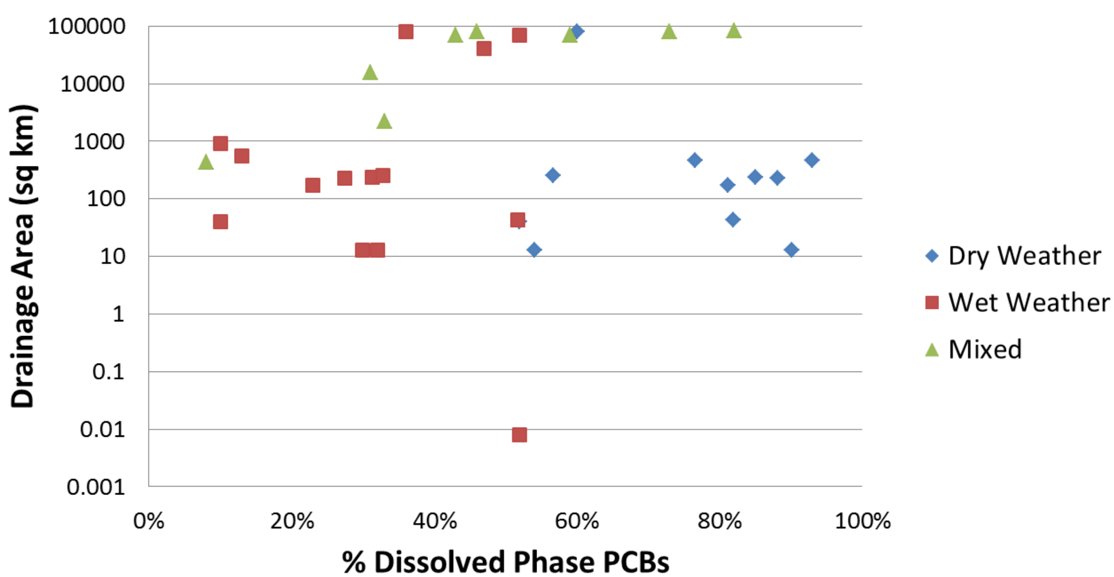

Figure 2-4. Summary graph of literature review case examples. Studies include: Marti and Armstrong, 1990; Quemerais et al., 1994; Verbrugge et al., 1995; Steuer et al., 1999; Foster et al., 2000a, 2000b; Ko and Baker, 2004; Gomez-Gutierrez et al, 2006; Hwang and Foster, 2008; Howell et al., 2011; Tlili et al., 2012; Bressy et al., 2012; RMP samples (Z4LA, Marsh Ck, North Richmond PS, Sunnyvale East Ch, Pulgas PS South, ESPS).

A second approach used to estimate dissolved phase PCBs in the Crescent watersheds involved manipulating the regional PCB and SSC data for other watersheds in the region and using the percentage impervious and old industrial area in each of those watersheds as a surrogate for estimating the dissolved phase in the Crescent watersheds (Table 2-8; see Appendix 1 for details about the method). This approach used data collected primarily in storm events and thus only represents the dissolved fraction during storm flow conditions. Based on this approach, estimates for the percentage of PCBs in the dissolved phase ranged between 13-18% for all three subwatersheds (Table 2-8).

Table 2-8. Estimates of dissolved phase PCBs for well-sampled watersheds (in white). The three Crescent watersheds were then estimated (in gray) based on the dissolved phase and imperviousness or old industrial relationships in the well-sampled watersheds.

						Estimated % Dissolved based on:	
Watershed	**PCB FWMC (ng/L)**	**Intercept**	**Dissolved**	**Impervious**	**Old Industrial**	**Impervious**	**Old Industrial**
Z4LA	14.7	1.4	10%	68%	9%		
Marsh Ck	1.97	0.177	9%	10%	0%		
N. Richmond PS	8.27	1.92	23%	62%	7%		
Sunnyvale East Ch	55.7	4.5	8%	59%	3%		
Pulgas Ck PS - South	137	30.6	22%	87%	46%		
ESPS WS	58.6	12.5	21%	76%	10%		
Emeryville Crescent North WS				71%	9%	17%	15%
ESPS WS				76%	10%	18%	15%
Temescal Ck WS				42%	7%	13%	14%

These dissolved phase estimates for the Crescent watersheds appear reasonable for storm flows relative to the results of the literature review, and so we recommend using the above estimates. The proportion of dissolved phase PCBs during non-storm flow is likely to be much greater based on data from the literature (52-93%) and we therefore recommend applying the median value from the literature review, or 81%.

Loadings Summary

Numerous improvements could be made to the loadings estimates for the Emeryville PMU and its subwatersheds (to be discussed later), but at this time, Table 2-9 summarizes our best estimates of the PCB loads transported to the PMU during different types of flow conditions, and the partitioning character of those loads. At this time, we estimate 214 g on average are transported to the PMU from the combined 18.9 sq km of area from the three primary watersheds (although see previous comments highlighting the land use basis for some of the estimates potentially causing a high bias). It is estimated that storm flows overwhelmingly deliver that load (94%), dominantly in the particulate phase (85% versus 15% dissolved). Although the 10-year storm event can transport approximately 11-16% equivalent of the average annual load, it is estimated that approximately 92% of the long-term load is transported during the dry season and storm events smaller than the 1:1 year return frequency. Non-storm related flows likely account for only about 6% of the total load and these flows are likely dominated by PCBs in the dissolved phase.

e. Projected Changes in Export to the PMU

The Municipal Regional Stormwater NPDES Permit includes provisions (C.11 and C.12) that require implementation of control measures to reduce PCBs in stormwater runoff. In January 2014, the Bay Area Stormwater Management Agencies Association (BASMAA) released a report detailing the pilot projects implemented or planned and findings to date (Geosyntec and EOA 2014). These projects were pilot-level only but intended to inform potential future management actions. Measures discussed in the report (Part B of the Integrated Management Report [IMR]) included some that were aimed to have more region-wide impact, and some that were focused in five pilot watershed areas, including ESPS Watershed.

Region-wide focused measures included training industrial inspectors to identify PCBs during inspections, and the development of planning tools, training, and BMP guidance to reduce off-site transport of PCBs in caulking materials during demolition and renovation of buildings. At the time of writing of the present report, industrial inspectors had been trained but there were no cases of PCBs identified in an industrial inspection, so there were no data to support an estimated load reduction in the Bay Area, let alone the Emeryville Crescent PMU, due to this control measure. Ensuring the effective reduction in off-site transport of PCBs in caulking materials could be fruitful in both the near and long-term in the ESPS Watershed where significant revitalization is likely to occur over the next several decades. The IMR estimated – based on the work of Klosterhaus et al. (2014) - that the average building contains 4.7 kg of PCBs, and baseline control measures are expected to capture 94% of that mass. Still, the 6% mass of PCBs released from an average building, then, is 282 g, or more than the average annual load to the entire Crescent. Key uncertainties exist in the IMR analysis, but the control of PCBs in caulking material presents one of the greatest opportunities to reduce PCB load to the Crescent.

Table 2-9. Summary table with key load and partitioning estimates during different types of flows.

			Annual PCB loads transported during different flow and partitioning characteristics (g)									
Watershed	Total Area (km^2)	Total Runoff Volume (Mm^3)	Total Annual Load - Best Estimate	During storms	During non-storm periods	Dry Season and storms smaller than the 1:1 year event	1:10 year event	Dissolved phase during storms[5]	Assoc. with particles <25 µm during storms[6]	Assoc. with particles 25-75 µm during storms[7]	Assoc. with particles >75 µm during storms[8]	Dissolved phase during non-storm periods[9]
Emeryville Crescent North WS	3.7	1.2	39	37	2.3	36	5	6	11	8	11	2
ESPS WS	4.6	1.5	87	82	5.2	80	12	13	26	18	25	4
Temescal Ck WS	10.6	3.3	88	83	5.3	81	12	11	29	18	25	4
Total for Margin Unit	18.9	6.0	214	201 (94%)[a]	13 (6%)[a]	197 (92%)[a]	30 (14%)[a]	30 (15%)[b]	66 (33%)[c]	44 (22%)[c]	62 (31%)[c]	10 (81%)[d]

[a] Percentage relative to the average annual load
[b] The percentage dissolved is watershed specific based on Table 2-8
[c] Percentage relative to the total storm-related annual load
[d] Percentage relative to the non-storm-related annual load

The IMR discusses five specific measures focused in the ESPS Watershed. First, several steps were completed to identify likely source properties. Potential sources in the ESPS Watershed were evaluated, sediment samples were collected nearby, and where high PCB concentrations are found, these sites will be referred to the regulatory agencies for cleanup and abatement. The referral process was being developed at the time of writing and no sources had yet been referred. At this time, it is not possible to estimate the load reduction due to this control measure; however, any load reduction attributable to cleanup of property in the ESPS Watershed would occur no sooner than 2019-2020 (and likely later).

Another potential measure identified but not implemented at the time of the report is cleaning out all of the wet wells in the ESPS annually, when deemed necessary. Prior to the IMR, two of the four wet wells were cleaned out annually, when necessary. During 7 years of cleanouts, it was estimated that 2.5 – 69 g of PCBs were removed per cleanout (depending on the amount of accumulated sediment in the wet wells). It is unclear at this time how much additional mass will be removed by cleaning out all four wet wells, but if the two additional wet wells trap sediment at the same rate as the two wells that were previously cleaned, it is conceivable that twice the mass of PCBs would be removed annually (5 – 138 g/year). The results of the pilot study will be made final by May 2017.

Diversion of ESPS influent during low flows to the nearby EBMUD wastewater treatment plant will be implemented starting in 2017; however, the plant does not have the capacity to accept ESPS flows during storms because of infiltration into its aging infrastructure during storm events. Pretreatment storage facilities could conceivably be constructed on nearby vacant land (e.g., under the MacArthur Freeway), and then pumped to EBMUD during non-peak flow times. At this time, no specific estimates of potential load reduction are available.

Specific measures being implemented and studied during this pilot phase include a bioretention unit along a street in the ESPS Watershed, and media filters placed at the pump station. The bioretention project is located near Peralta St between 24th and 30th streets and includes six Filterra tree well treatment units. The units have been completed and are estimated to capture 0.124 g of PCBs annually. Design plans for the media filters at ESPS have been completed but the filters have not yet been constructed. It will consist of two filters, each with a capacity of approximately 30 gallons per minute. The estimated load reduction resulting from the media filters is 0.188 g of PCBs annually. These pilot-level studies may provide a basis for future management actions and be replicated in other watersheds. It is also possible more PCB controls will be installed in the ESPS Watershed, but there is currently nothing planned. The results of the pilot studies will be made final by May 2017.

In addition to the pilot project studies summarized in the IMR, SFEI is currently developing on its own initiative a planning tool intended to help aid in the identification of the best locations for green infrastructure. GreenPlan-IT (http://greenplanit.sfei.org/) is a geospatial modeling tool to help municipalities evaluate management alternatives for green infrastructure. San Mateo and San Jose have already used the toolkit successfully (http://greenplanit.sfei.org/books/toolkit-technical-memo). The City of Oakland is currently working with SFEI to model flow and PCB transport through the ESPS Watershed and to apply the GreenPlan-IT toolkit to guide future implementation of green infrastructure specifically to reduce PCB export to the Bay. That effort will help to refine estimates of load reduction possibilities in the subwatershed based on green infrastructure implementation, and is expected to be completed in mid-2017.

In summary, near-term reduction in PCB loads are due to pilot-level management actions and therefore small (totaling 0.3 g annually due to the pump station media filters and bioretention tree well filters) or not yet estimated due to various information gaps or implementation hurdles (trained industrial inspectors to identify PCBs, control measures to reduce off-site transport of PCBs in caulking materials, identification of source properties requiring abatement, cleaning of all the pump station wet wells annually, and diversion of effluent from the pump station). Estimates of longer-term reduction in PCB loads due to green infrastructure scenarios are currently in development (GreenPlan-IT, SFEI) and will be better quantified as the current pilot projects are implemented, studied, and in turn, help to guide the long-term PCB management strategy. Water Board staff have suggested that PCB load reduction in the Crescent watersheds is likely to be in the 5-25% range in the next 5-8 years; a load reduction of 12% in the next five years would be a significant achievement.

In light of management actions currently in an early phase of a longer-term effort, and the longer-term TMDL goal of a 90% reduction in PCB load, this analysis considers a range of possible reduction levels in the PMU mass budget. The levels considered include a 25%, 50% and 75% reduction in PCB loads to the PMU.

f. Monitoring Recommendations

Over the past 17 years, the Sources Pathways and Loadings Workgroup has developed and implemented a number of field-intensive monitoring protocols designed to characterize concentrations, particle ratios, and watershed loadings during storms. In addition, most recently, the Workgroup has been developing and testing a series of remote sampling techniques that, if successful, may reduce the field effort required for each individual sample, potentially allowing for a greater number of samples with a fixed budget or reduced overall budget. Each of these monitoring protocols is tailored to suit specific questions and needs (Table 2-10). Presently, these same monitoring designs are being explored for use in measuring trends in response to management efforts.

Preliminary Data Gathering

The main near-term data weaknesses associated with the loading estimates are the lack of any kind of monitoring data during storms in the Emeryville Crescent North Watershed and Temescal Creek Watershed. Another major weakness is the lack of information on PCBs in relation to particle size or in the dissolved fraction. In the near-term these data gaps can be filled using either the wet weather single storm reconnaissance (composite) sampling design or the wet weather single storm reconnaissance (discrete) sampling design. The discrete method is slightly better in that we would get some idea of how variable the relationships between flow and PCBs and dissolved or particulate phase may be over a storm. This type of monitoring could be carried out as part of the pollutants of concern monitoring study that was first conducted in WY 2011 and then has been ongoing since WY 2015 (McKee et al., 2016; Gilbreath et al., in review). If these data were coupled with stage and flow measurement, we could determine a storm-specific load which would help to provide a reality check on the annual-scale loads estimates for each of the PMU sub-watersheds.

Long-term Monitoring

A monitoring program for accurate loads measurements was designed and implemented in the North Richmond Pump Station (Hunt et al., 2012; Gilbreath et al., 2015). This methodology included measurement of pump speed and duration, continuous measurement of turbidity and stage in a representative wet well, a knowledge of pump efficiency curves, and discrete sampling for laboratory analysis of pollutant concentrations including PCBs and other pollutants of interest. Although each station is configured uniquely, the methodology and lessons learned from the experience of monitoring the North Richmond Pump Station over a two-year period provide a reasonable blueprint for monitoring design. The key question for implementation of this level of effort (the highest level as identified in Table 2-10) is whether the uncertainties associated with the planning level modeling effort of fate within the PMU can be resolved by obtaining continuous (at scales of minutes) estimates of flow and PCB load over wet season or multiple wet season timescales. And even if these would be useful data, are the time and effort taken to obtain them from the ESPS Watershed and the other attending subwatersheds of Emeryville Crescent going to change our understanding of the processes of pollutant uptake in the Bay margin? These questions need to be reconciled as we learn more about the Crescent after a first phase of data collection or as we continue to work on other PMUs such as San Leandro Bay where further insights will be gained as to the sensitivity of the model of Bay margin processes to data gaps. At this time no tributary data gathering is recommended but further consideration could be given to tributary monitoring as the answers to these types of questions emerge. If further watershed data collection is warranted, it may be expensive and require funding from additional sources beyond the RMP.

Table 2-10. Monitoring protocols available to support characterization of concentrations, phase distribution, particle ratios, or PCB loadings during storms.

Data uses	Name of protocol				
	Remote sampler (Walling tube/ Hamlin	Wet weather single storm reconnaissance (composite)	Wet weather single storm reconnaissance (discrete) coupled with stage and flow measurement	Wet weather multi-storm discrete) coupled with stage and flow measurement	Wet weather multi-storm discrete) coupled with stage, flow, and turbidity measurement
	Relative level of effort				
	Low	Medium	Medium-high	High	Very high
	Potential for use for each question				
Trends	Maybe	Maybe	Maybe	Yes (lower certainty)	Yes (high certainty)
Relative PMU sub-watershed rankings	Yes	Yes	Yes	Yes	Yes
Quantification of PCB concentrations on sediment size fractions	Yes	Yes	Yes	Yes	Yes
Quantification of dissolved phase		Lower certainty	Lower certainty	High certainty	High certainty
Support for RWSM to estimate loads		Calibration only	Calibration only	Calibration only	Calibration and verification
Measured storm specific loads			Yes	Yes	Yes
Support for dynamic model (e.g. SWMM) to estimate continuous tidal loads estimates			Calibration only	Calibration only	Calibration and verification
Measured wet season loads				Yes (lower certainty)	Yes (high certainty)
Measured continuous loads estimates					Yes (high certainty)

Another group within the RMP, the Small Tributaries Loadings Strategy Team, is presently grappling with how to design a trends monitoring program for urban creeks and drainage systems to assess changes in concentrations and loadings associated with management efforts. The work is still in the development phase with a draft report planned for late 2017. With input from several key technical advisors, the Strategy Team is presently envisioning a period of data collection in several key watersheds over the next 2 to 3 wet seasons targeted at increasing the representativeness of existing datasets to a wide variety of flow conditions and pollutant release processes. Such data should provide a better basis for the final design of the trends monitoring protocols. Ideally, these monitoring locations would be coupled with watersheds where it is likely that a greater level of management effort will be occurring over the next 5 to 10 years so that a robust baseline is generated. Alternatively, monitoring associated with trends measurement could be prioritized for areas upstream from PMUs where having an understanding of change in mass loads would help us to understand any trends observed in the sediment or biota within the PMU. The best case scenario would be where all three of these things are coupled together: management effort in the watershed, a trends monitoring program downstream from where that management effort is going on, and intensified sampling in the PMU to track change in the Bay through time.

Monitoring Locations

The question as to whether a subset or all three watersheds need to be monitored should be considered in relation to the results of the initial modeling efforts in the PMU. In relation to a sensitivity analysis of the modeling effort, what are the impacts of the uncertainty in the data that were input into the model and what are the chances of a monitoring program reducing those weaknesses with a reasonable level of effort? The data input into the model included the following:

- estimates of load in relation to varying storm sizes assuming a seven hour tidal window;
- estimates of the fraction of that load in dissolved phase; and
- estimates of the fraction of that load that was delivered in several particle sizes.

All three of these aspects of the loading estimates are currently very weak for the ESPS Watershed and even weaker for the other two Crescent watersheds. It would be a relatively simple effort using either a remote sampler (Walling tube/ Hamlin) or the wet weather single storm reconnaissance (composite) protocols to gather information to verify the assumption that Emeryville Crescent North and Temescal Creek watersheds have lower pollution levels than ESPS Watershed. This would be the first line of evidence that the relative annual loading estimates are reasonable. Beyond that, and only if warranted, a much larger effort could be implemented to characterize concentrations and loads at each of these watersheds with reasonable certainty. This should only be done if the sensitivity analysis of the Bay margin model suggests improved loadings from the watersheds as a priority data gap.

The decision on how to monitor all three watersheds draining to the Crescent should be related to the priority information needs. It seems likely that the best method for estimating loads would be the calibration of a dynamic simulation model such as SWMM. Thus the monitoring effort chosen for each of the three watersheds should be at least sufficient to calibrate such a model. The minimum monitoring method suitable for calibrating a dynamic simulation model is the wet weather multi-storm discrete sampling protocol coupled with stage and flow measurement (Table 2-10). Implementing such a protocol over a single wet season in all three watersheds would provide sufficient data for estimating loads at timescales shorter than a single tidal cycle using a model like SWMM. Obviously, if more years of data were collected, a greater accuracy would be achieved but with diminishing returns. Since data already exist for ESPS Watershed, a lower level of effort can be applied in that system that includes just enough data to evaluate concentrations of PCBs in relation to particle size and in the dissolved fraction. For the other two watersheds, samples could be collected appropriately for evaluation of PCB concentrations in relation to particle size and dissolved phase.

Summary

There are a number of weaknesses in the loading data for the Crescent as summarized in this section. However, at this time, we are not recommending any further tributary watershed data collection. The discussion provided here is meant to provide a framework in the event that monitoring of tissue and sediment in the PMU and further sensitivity analysis of the coupling between watershed loads fate of PCBs in the margin reveal the need for a better understanding of loading.

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3. Initial Retention in the PMU

a. Factors influencing retention

Figure 3-1 illustrates a general conceptual model of sediment associated contaminant fate and delivery in margin areas such as the Emeryville Crescent ("the Crescent"), with delivery via tributary channels to the water's edge, much of the time in the intertidal zone, and subsequent deposition, resuspension, and eventual (partial) transport out of the area. This section will focus on the short-term fate of discharged loads, and the likely deposition zones for discharges.

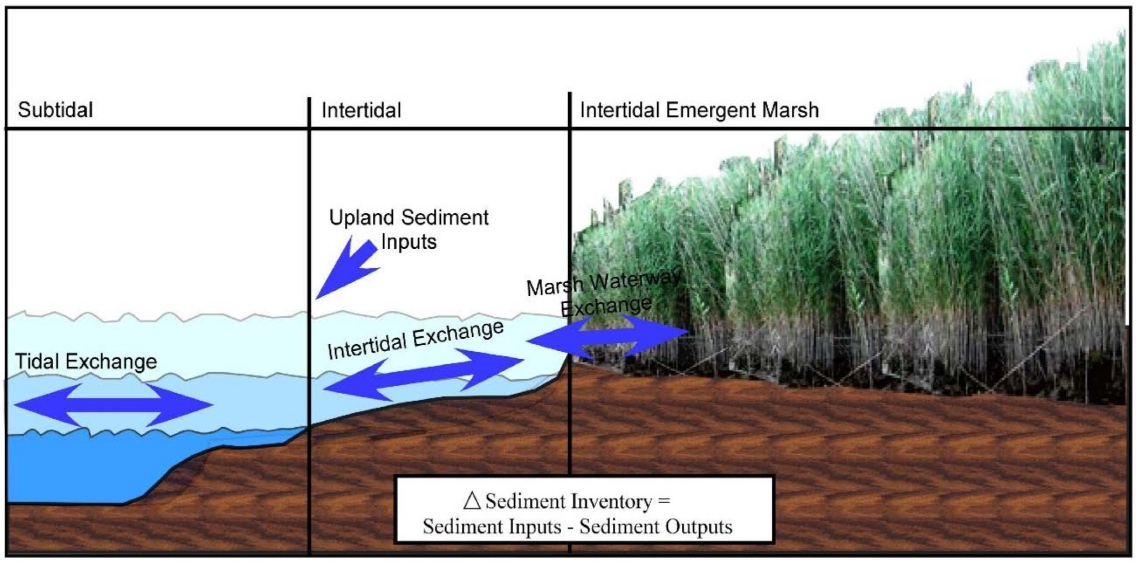

Figure 3-1. General conceptual illustration of margin sediment fate

i. Tidal elevation

Numerous event-specific factors will affect the location of initial discharge to the Crescent along with the percentage of PCB loads retained within the area. One major factor causing differences of up to several hundred meters in the location of initial entry into the PMU waters is the portion of the tidal cycle at which the discharge occurs. Although there will also be spring-neap tidal cycles affecting the discharge, daily average diurnal tidal cycle statistics represent a reasonable starting point for characterizing the probable average locations of discharge over multiple decades.

Figure 3-2 illustrates the MHHW (mean higher high water), MHW (mean high water), MSL (mean sea level), MLW (mean low water), and (mean lower low water) MLLW tidal elevations within the Crescent, with about 500 m separating the points of entry for Temescal and ESPS/Emeryville North watersheds at MHHW vs MLLW. Although there has been a study linking lunar phases to atmospheric pressure and thus precipitation probability (Kohyama and Wallace 2016), the timing and duration of storm events is largely independent of tidal influences, so the occurrence of a discharge at any given tidal elevation is probably best modeled as a random function of time. The probability of discharge at any given tidal elevation is not uniform however; given the sinusoidal pattern of tides, elevations near high and low slack are disproportionately included. If we divide each tidal cycle into four equal duration periods, max flood, high, max ebb, and low, the periods around high and low slack will each account for one quarter of the total time, but around 15% of the total elevation range. Thus there is a slight propensity towards discharge at the upper and lower ends of tidal elevation under a random timing assumption.

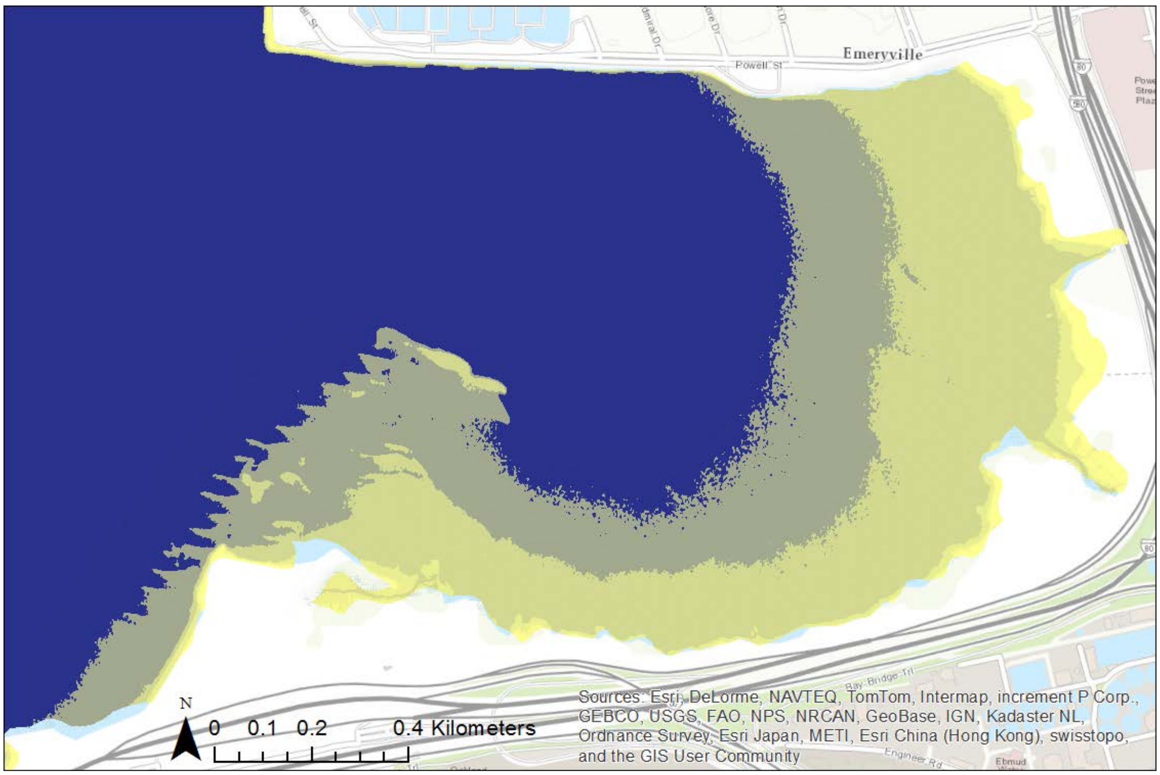

Figure 3-2. Tidal datums in the Crescent. MLLW, MLW, MSL, MHW, and MHHW indicated by colored contours, from darkest (blue) to lightest (yellow), respectively.

ii. Settling rates

In addition to the timing and thus location of discharge, the propensity of discharged loads to remain in the Crescent will depend on the characteristics of the discharged loads. A settling experiment in a previous study of stormwater samples from Hayward Z4LA and a Richmond storm drain (Yee and McKee 2010) indicated that between approximately 30% to 70% (towards the higher end at higher flows) of PCBs would settle out of a 30 cm settling column within 20 minutes, or roughly 1 m/hr settling. Typically half to two-thirds of that total (again on the higher end for higher flow and higher concentration samples) settled out within 2 minutes (10 m/hr).

Given tidal currents and wind waves in the natural environment, a laboratory settling column is relatively quiescent compared to open Bay waters much of the time. Other processes such as flocculation of freshwater runoff entering a saline receiving water or a buoyant plume of freshwater flow carrying further out in the Crescent will be highly event-dependent and hard to anticipate in terms of net effects without *in situ* empirical data. However, the laboratory settling rates obtained represent a simplistic (likely upper bound) estimate of likely deposition in the near field of any discharge. Much of the Crescent is very shallow, less than 1 m deep at MLLW. Even as the water depth (and thus the entry point into the receiving water) varies during each tidal cycle, the vertical distance required for settling to the bottom remains largely unchanged, with the bottom slope approximately constant through much of the intertidal zone (as seen in fairly even spacing of the MSL, MWL, and MLLW tidal elevations from north to south along the eastern shore in Figure 3-2).

iii. Transport

Another major factor to consider in predicting the short-term fate of pollutants and sediment discharged to the Crescent is the speed of advective flows leaving the area. The ebb tide, occurring over around 6 hours, likely represents the largest pathway for removal, at least for fine suspended sediment and dissolved phase contaminants. It occurs twice daily, largely independent of any watershed flows, so for the majority of days in each year where there is only baseflow, tidal transport still occurs. Even for coarser-grained sediment only mobilized by large freshwater flow events or strong wave resuspension, such events would require concurrent outgoing tides to export appreciable mass before this coarser sediment settles out again. Although the volume in the Crescent at MLLW after an ebb is only 1/6 that at MHHW, a proportion of that will return on the subsequent flood. An estimate of the returning portion will be discussed in a later section on an exploratory hydrodynamic model of the Crescent.

b. Comparison to Other San Francisco Bay Margin Areas

Comparisons to other PCB-contaminated areas within the Bay are illustrative of these factors. Seaplane Lagoon at Naval Air Station (NAS) Alameda represents one end of the spectrum (Figure 3-3). It is a small (4.5×10^5 m^2), highly-enclosed (only one 250 m wide opening behind a seawall), and relatively deep (6-7 m at MLLW) site, compared to more natural shorelines in the Bay, where depths often do not exceed 2 to 3 m for several hundred meters from shore. Stormwater and industrial wastewater from NAS Alameda were discharged to Seaplane Lagoon from outfalls in the northeast and northwest corners of the lagoon, resulting in contamination by radium and PCBs, among other contaminants (Love et al., 2003, U.S. Navy, 2008). The NAS Alameda was only 6.6×10^5 m^2 in area, slightly larger than the receiving water, so runoff discharge would likely be only slightly greater in volume than direct precipitation to the lagoon, with low velocity, due to entry into a steep-shored deep receiving water. As a result, the PCB contamination gradients from the outfalls of NAS Alameda are short and steep (dropping to near background within <100 m) (Figure 3-3), with little redistribution within the site due to its depth (favoring net accretion) combined with limited wave and current action resulting from the constructed seawall.

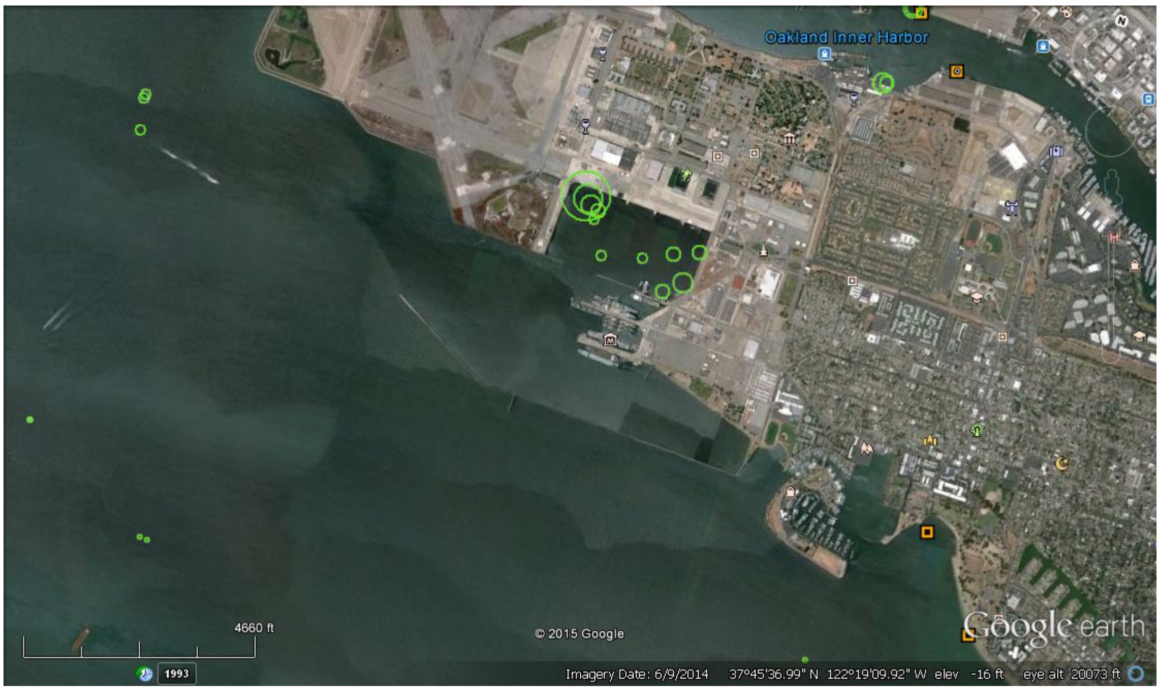

Figure 3-3. Bubble plot of sediment PCB concentration distributions in and near Seaplane Lagoon, NAS Alameda.

Hunters Point Shipyard (HPS) South Basin represents an environment physically similar in some aspects to the Crescent (U.S. Navy 2007). South Basin is U-shaped, with the width of its opening of a similar magnitude to the length of the embayment, and freshwater discharge from its upper end. Its maximum depth is 2 m, with a gradual shoreline slope in much of the intertidal area. Most freshwater discharge occurs from Yosemite Creek, at the northwest end of the embayment. However, unlike the Crescent, where the freshwater discharge is presumed to deliver much of the primary PCB source, much of the PCB contamination source at HPS originated from landfills present during different periods. One existed at the northwest near the mouth of Yosemite Creek, and a more recent one at the northeast shoreline of South Basin, both of which received various wastes including PCB-containing transformer oils during their periods of operation. The primary advective transport in the surface water would therefore occur with tidal flows concurrent with resuspension events, or with tidal flows supplemented by stormwater for Yosemite Creek. PCB gradients in this area are longer than at Seaplane Lagoon (Figure 3-4), likely due to the shallow shoreline and gradual slope, allowing greater resuspension and tidal dispersion of sediment. The contamination contours in the area near the mouth of Yosemite Creek are somewhat stretched out relative to those from the more recent (NE) landfill without major freshwater inputs (Figure 3-5), suggesting some influence of freshwater and tidal flows via the channel.

Figure 3-4. Bubble plot of sediment PCB concentration distributions in and near Hunters Point Shipyard South Basin.

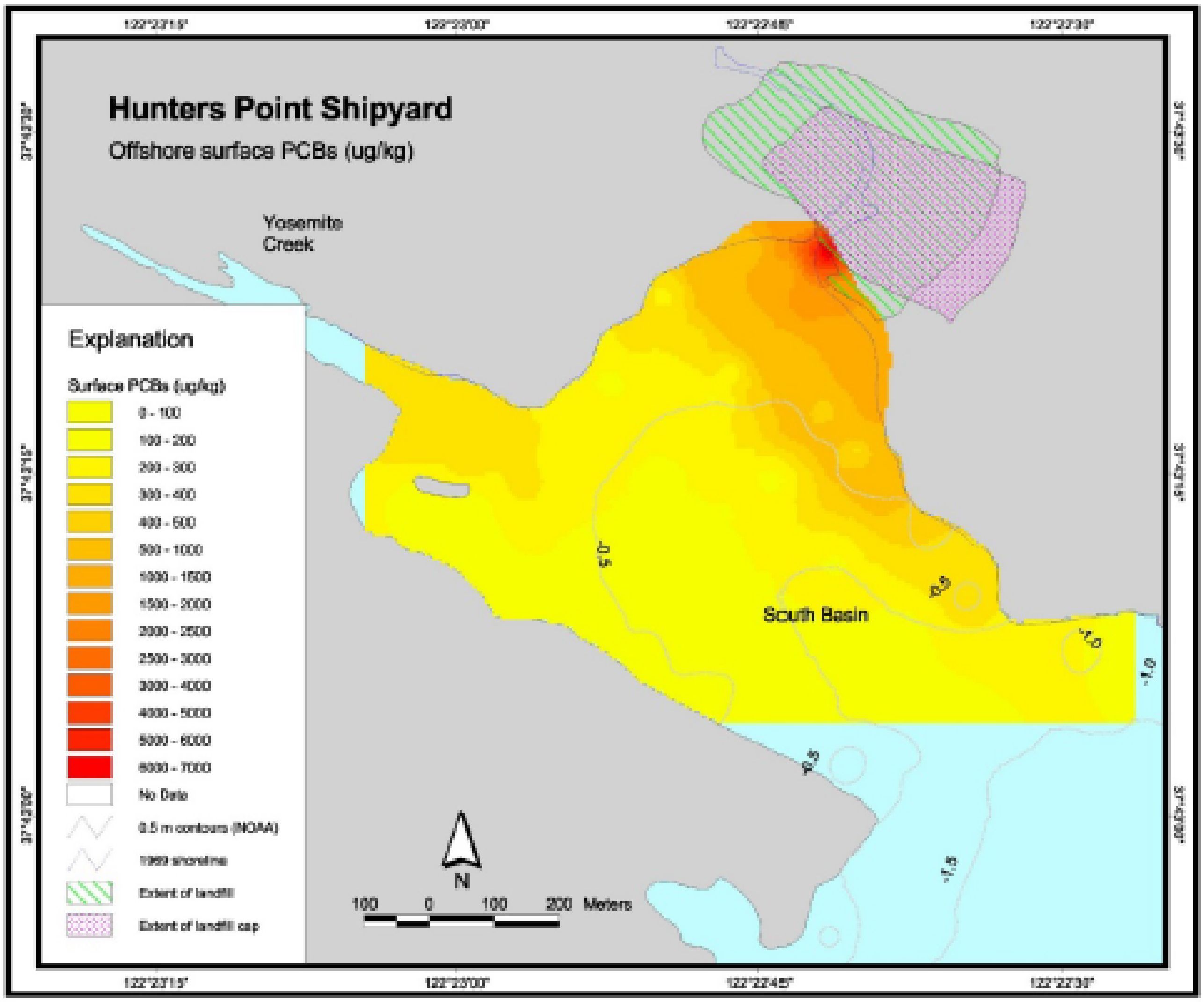

Figure 3-5. Contour map of surface sediment PCB contamination in and near Hunters Point Shipyard. Note slight elongation of contamination field extending from Yosemite Creek.

San Leandro Bay (SLB) is somewhat similar to Seaplane Lagoon in having a very constricted connection to the Bay, and thus being highly protected from strong waves and tidal currents in its interior. However, unlike Seaplane Lagoon, it receives discharge from a moderately large upland watershed and is shallow though much of its area (Daum et al. 2000). Numerous smaller watersheds also discharge to SLB, with many of them including older industrial areas with known or potential past PCB usage or disposal, include a Pacific Union yard along Damon Slough currently being investigated by EPA. As such, it may present a very complex picture of PCB sources to deconvolute. Nonetheless, there are some hints of possible gradients extending away from upland sources, for example a drop in PCBs with distance from the mouth of San Leandro Creek (Figure 3-6). Similarly, there is a moderately stretched out gradient away from a highly contaminated site near Coast Guard Island in Alameda Channel, where tidal currents and constricted area for dispersion may extend observed gradients.

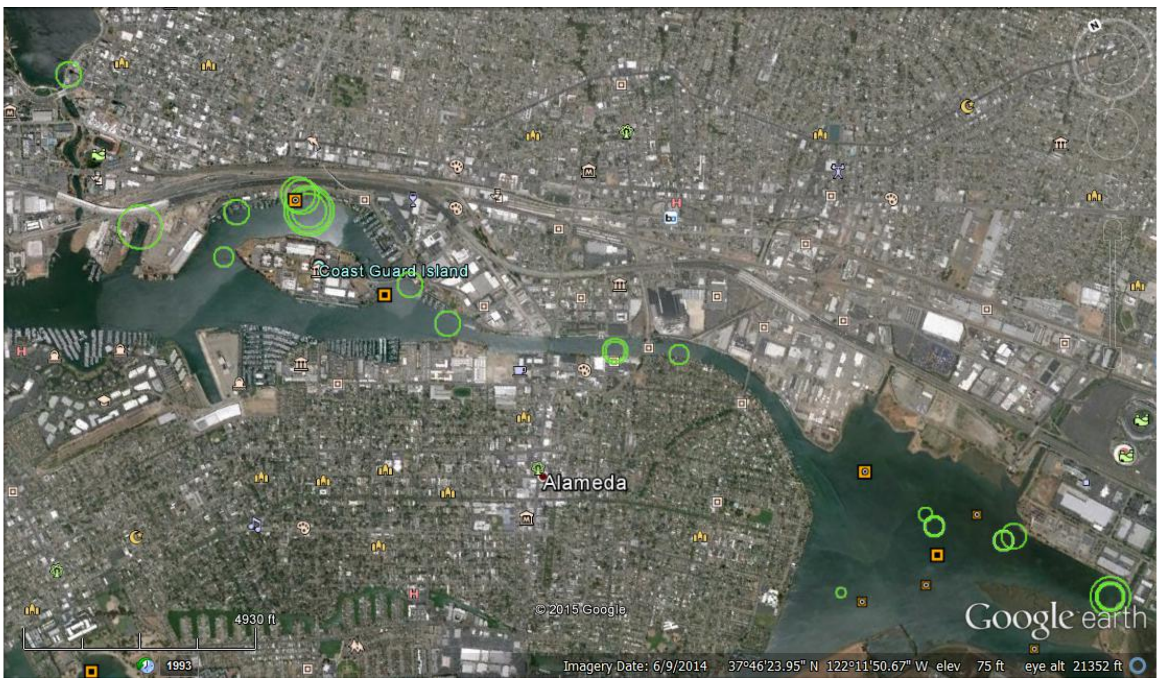

Figure 3-6. Bubble plot of sediment PCB concentration distributions in and near San Leandro Bay.

Steinberger Slough represents another end of the spectrum, with a very narrow water body (a long, snaking tidal slough) receiving discharge from a variety of small and large watersheds. This area includes some older industrial areas bordering the Bay shoreline. Much of the area has been converted to newer commercial or residential developments, but includes sites such as Delta Star, an electrical equipment facility that provided some PCB-containing products under its previous operator, H.K. Porter (SFBRWQCB, 1999). There are other potential PCB sources in the surrounding formerly industrial areas, so like San Leandro Bay, it may not be a simple case of a single PCB source dominating. However, the large upland watersheds and relatively narrow receiving water in the immediate vicinity of the likely discharges would result in more pronounced outward flow and less dispersion during storm events as compared to areas of the Bay with discharge to more open shorelines and wide-mouthed embayments such as the Crescent. The relatively slower drop off in PCB concentrations with distance as compared to other sites (Figure 3-7) is suggestive of this greater advective transport and reduced dilution or dispersion of contamination until reaching the open Bay, with evidence of greater dilution or dispersion in the direction of a larger receiving water (i.e., the steeper gradient decreasing towards the Port of Redwood City). The details of PCB sources and the directions of stormwater and tidal flows are likely complex in this area, but the PCB distribution at least is in concurrence with our expectations for a receiving water with more channelized flow characteristics.

Figure 3-7. Bubble plot of sediment PCB concentration distributions in and near Steinberger Slough.

c. Hydrodynamic modeling

Several exploratory analyses have been carried out using a hydrodynamic model. The simulation is based on a SUNTANS hydrodynamic model (Holleman et al. 2013), and includes tidal forcing in the coastal ocean, outflows from major rivers, and a simplified wind field. Based on these inputs, the model predicts sea surface height and depth-averaged current velocity. While a model specifically calibrated for the Crescent is beyond the scope of the present study, this SUNTANS model has been validated for tides and currents at a wide range of stations in Central Bay, South Bay and San Pablo Bay, and captures the Crescent with roughly 100 m grid resolution. The model output has been analyzed for two specific purposes, (i) extracting local tidal datums for the Crescent, and (ii) estimating tidal velocities and transport within the Crescent.

Tidal datums have been extracted from a year of model output for a point centered on the mouth of the Crescent. These elevations are tied to the NAVD88 vertical datum, allowing for direct comparison to tide gages around the Bay. The results are summarized in Table 3-1, which also includes comparable tidal datums at the San Francisco Fort Point tide gage. The results show a small super-elevation of the mean water level, and an 8% amplification in mean tidal range (MHW-MLW).

Table 3-1. Tidal datums for Emeryville Crescent versus Fort Point (mouth of SF Bay).

Datum	**Crescent (m NAVD88)**	**Fort Point (m NAVD88)**
MLLW	0.00	0.02
MLW	0.32	0.36
MSL	0.99	0.97
MHW	1.67	1.61
MHHW	1.85	1.80

Velocity data have been extracted from the model for a period of 15 days (March 29, 2016 to April 13, 2016) in order to average over spring-neap variations in tides. The largest velocities occur near the mouth of the Crescent on the deeper (northern) side (Figure 3-8). Tides here are approximately symmetric, with no obvious flood or ebb dominance. Current speeds range from a neap-tide small ebb of 200 m/h, to a neap-tide large ebb of 400 m/h and spring-tide large ebb of 700 m/h. Similar metrics for a site in the intertidal eastern end of the Crescent show transient, peaky velocities, with maximum speeds about 30% lower than the speeds at the mouth, but average speeds (averaged over the portion of the ebb when the area is inundated) about 50% lower than at the mouth.

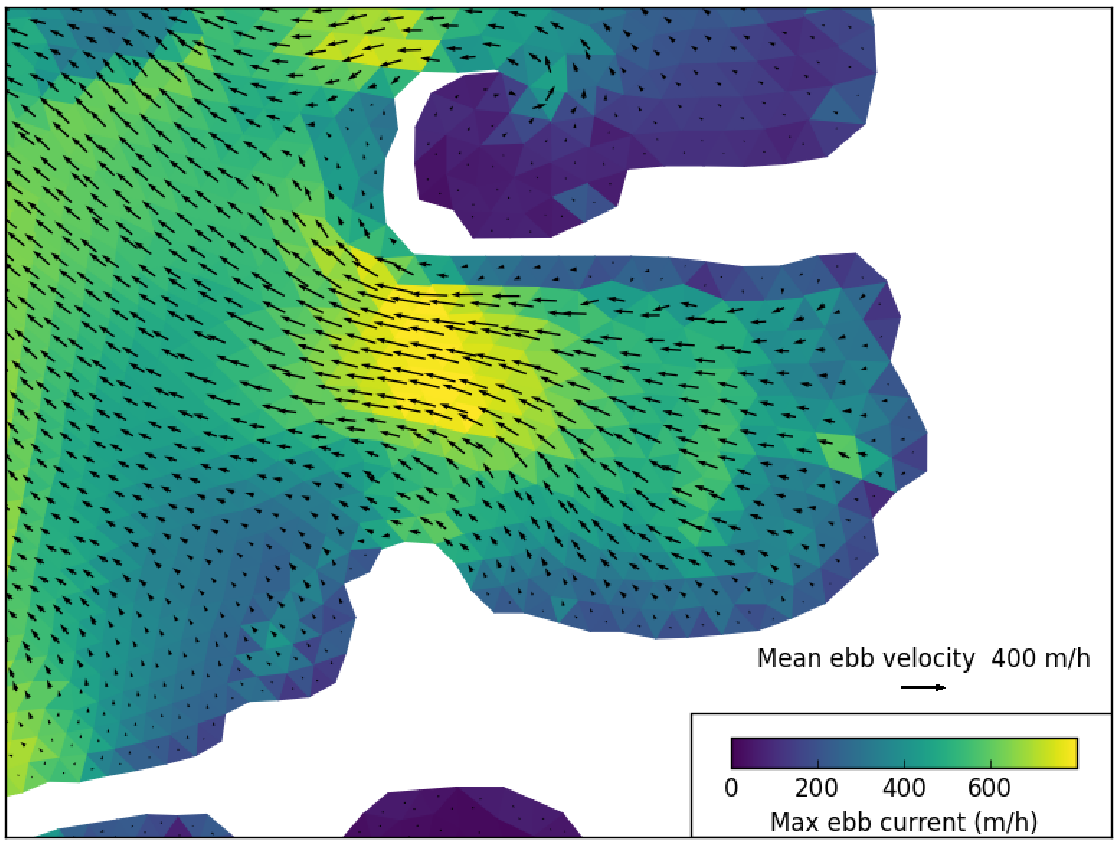

Figure 3-8. Mean ebb velocity while submerged for various points in Emeryville Crescent.

In many tidal flows the mean transport over the course of a full flood-ebb tidal cycle is much smaller than the transport during a single ebb since the subsequent flood tide will "unwind" the transport in the ebb. When spatial variation in currents is small, the long-term mean of the velocity field is a good approximation to this mean transport. In the case of the Crescent, currents vary inside versus outside the Crescent, and it is necessary to more explicitly follow the path of a water parcel advected by the currents over a tidal cycle. Figure 3-9 shows the result of such an analysis over an ebb-flood cycle during intermediate spring-neap conditions. The fraction of trajectories which are still within the Crescent at the end of the tidal cycle implies that about 30% of the Crescent's volume is retained, primarily the water mass which started in the shallowest portions of the Crescent (black circles). Most of the water mass exits the Crescent and is advected southward by strong residual velocities outside the Crescent. Those parcels which do reenter the Crescent systematically shift clockwise within the crescent (i.e., the spatial distribution of the black circles versus the red squares within the Crescent). The green-yellow transition in the background of the figure denotes the intertidal-subtidal transition at spring tides.

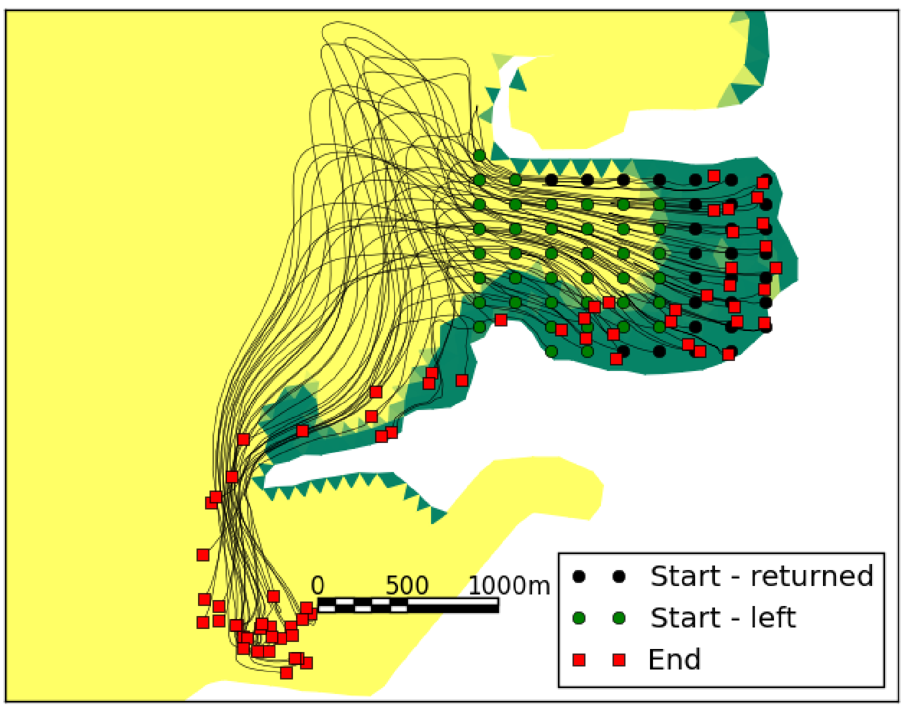

Figure 3-9. Tidal cycle trajectory for various points in Emeryville Crescent for start and end points at high slack. Approximately 30% of the water volume remains in or returns to Emeryville Crescent.

d. Retention in moderate and large storms

The distance that suspended sediment in stormwater is carried will be highly dependent on the volume and velocity of the discharge, and the velocity of the receiving water (e.g., whether it is a high or low slack, flood, or ebb tide). Assuming that the discharge is occurring into a static water body (a slack tide) gives us at least a sense of scale for the likely discharge velocity extending into the Crescent. We consider the cases of 1 year and 10 year annual return interval (ARI) rainfall events to derive reasonable bounds for the volumes of discharge to the Crescent.

The 24 hour rainfall from a 1 year ARI storm event obtained from the NOAA record for Oakland indicates precipitation of about 1.9 inches (Table 2). Data on rainfall from the Oakland Museum (supplemented by rain gauge data from Oakland Airport and Alameda to fill in gaps) over a 40 year period (1970 to 2010) suggest a slightly lower but similar rainfall for the 40th largest day, 1.75 inches. Using runoff coefficients for the various land uses and running the RWSM, we estimated daily outflows of 117,000 m^3 from the ESPS/Emeryville North watershed, and 475,000 m^3 in total from all the watersheds in the Crescent for the 1 year ARI rainfall. A 10 year ARI 24 hour storm event (a threshold above which there are typically only 4 events in a 40 year history) will deliver about double the volume, 243,000 m^3 per day for ESPS/Emeryville North, and 985,000 m^3 for all of the Crescent.

Interestingly, the cumulative rainfall of all events greater than the 1 year ARI event in the 40 year Oakland Museum rain gauge data series combined accounts for only 8% of the 40 year total. Thus, although these events individually deliver relatively large volumes of discharge with potentially large short-term impacts, considered on a multi-decadal basis, missing these largest events may have a relatively small impact on estimated loads, at least for highly impervious urbanized watersheds. The same might not be said for more pervious watersheds, where small precipitation events are simply absorbed into the landscape. There are also non-linear relationships between runoff and sediment loads for pervious watersheds, with higher flows delivering sediment disproportionate to their volume. However, the same would not be expected for constructed stormwater conveyances, which are generally designed to be self-cleaning. Unlike situations such as the New Almaden Mining District where landslides and bank erosion could result in increasing (and seemingly limitless, at least in the short term) delivery of mercury contaminated sediment with increasing flow, PCBs in urban conveyances are likely source-limited in the short term. Once recent build-ups are scoured, additional flow may deliver lower (perhaps negligible) additional loads until sufficient time has occurred for further release and build up.

The daily volume delivered to the Crescent in a 1 year ARI event is slightly less than the volume in the Crescent at MLLW (580,000 m^3). Thus even if the delivery of an entire 1 year ARI 24 hour event's discharge occurred in the hours immediately preceding and around low ebb, the discharged volume would still be approximately contained within the Crescent. Some dispersion and dilution would occur with the outermost waters delivered, but it is likely that much of the very rapid- (~10 m/hr) and moderately-rapid (~1 m/hr) settling sediment containing the majority of PCBs measured in Hayward and Richmond previously reported (Yee and McKee 2010) would settle out before reaching the edge of the Crescent. These settling rates are much larger than those reported for the previous whole Bay one-box model, but this may be reasonable; those average settling rates represent sediment that can remain largely suspended day-to-day in the Bay simply through typical tidal and wave action, whereas storm discharges represent episodic higher velocity discharges, of which only a portion may remain suspended under normal tidal and wave action.

The delivery of a 1 year ARI daily total discharge in the last hours of an ebb tide are not highly probable however. An estimated rainfall of 1.85 inches over 3 hours represents a 25 year ARI event, and 1.87 inches over 6 hours represents a 5 year ARI event. Although the trajectory of water starting from the MLLW line at high slack (Figure 3-9) does exit the Crescent, that travel path does not apply to water starting from that location later in the tidal cycle. Water discharged at the MLLW line at low slack would quickly be sent back with the incoming flood tide. Waters discharged earlier in the tidal cycle start further east, and thus much of that water also returns on the subsequent flood tide. Net export would require material at the MLLW line to roughly remain in place (i.e., settled out) during flood tide then require resuspension of sediment in place at that point during ebb tide (beneath ~1 m of water at high slack), with sufficient energy to keep it suspended until exit from the Crescent.

The volume of water delivered in a 10 year ARI daily rainfall event, 985,000 m^3, is nearly double the volume of the Crescent at MLLW. However, the probability that it would occur on a single tidal cycle to push out of the Crescent is very low. The 10 year ARI daily rainfall, 3.75 inches, is greater than a 1000 year ARI for 3 hour total event (3.07 inches), and greater than a 200 year ARI for a 6 hour event total (3.63 inches). Thus although half of the volume of a 10 year ARI would be forced out of the Crescent if delivered all at once, it is highly unlikely that it could occur within 6 hours to be discharged on a single tidal ebb. It would be more likely to occur at a lower intensity, requiring two or more tidal cycles to disperse and export the discharge.

The unsettled fraction (<1 m/hr settling rate) in the BMP evaluation project (Yee and McKee 2010), 30% to 70% of stormwater total PCBs, provides an alternative reasonable estimate of the portion of PCB loads that might not be retained within the Crescent in the short term. Although this unsettled fraction may not be immediately delivered out of the area, while it remains unsettled, it can continuously disperse, dilute, and be advectively transported, and thus eventually be carried out of the Crescent after a number of tidal cycles. Quantifying the export rate for this fraction would require hydrodynamic modeling beyond the scope of this effort, but a roughly calibrated (focused mainly on generating approximately correct tidal heights) SUNTANS simulation of the Crescent suggests that about 30%

of the volume in the Crescent at high tide returns on the subsequent flood. Therefore, an assumption of 70% loss of any dissolved or unsettled fraction on each tidal cycle appears to be a reasonable estimate. After 10 tidal cycles (5 days), only 3% of this initial unsettled fraction would remain, so it may be reasonable to approximate that this unsettled fraction effectively was immediately lost from the Crescent. A simple mass budget model in the following section will evaluate the impacts of various assumptions for PCB loads and concentrations inside and outside of the Crescent on net tidal export.

e. Hypothesized initial deposition pattern

We have not found data on gradients of PCBs in sediment in or around the Crescent (although an individual point measured for the Bay Protection and Toxic Cleanup Program [BPTCP] in the southeast [in the intertidal portion near the entry from the ESPS and Emeryville North watersheds] had total PCBs at 86 ng/g - higher than typical for nearby open water areas of the Bay), so here we attempt to make educated guesses as to where the highest concentrations might be found, in order to design future monitoring efforts. As mentioned previously, due to the sinusoidal pattern of tidal cycles, the time spent at the upper and lower and end of the tidal range is greater than would be obtained from a uniform probability distribution. Thus the location of initial discharge to the Crescent will be somewhat weighted toward elevations nearer MHW and MLW, if we assume discharges will occur at random times.

With 30% to 70% of the PCBs settling at a rate of 1 m/hr or more in lab experiments, and half to 2/3 of that fraction settling at over 10 m/hr, a large proportion of the total PCBs in sediment from any given discharge would be expected to rapidly drop out of the water column and be found near their entry point in the PMU. This fast settling fraction would especially be expected to be found in the near field; most of the Crescent is less than 1 m depth at MLLW, and even at higher tides, many discharges will occur at the edge of the water line in the shallow sloped intertidal zone (i.e., discharged into a depth < 1 m), and thus require little vertical settling distance to reach the bottom. Thus the axial travel distance of discharges in the first 0.1 hour (6 minutes) and 1 hour after entry can provide hints of the likely location of the majority of discharged contaminated sediment.

In order to estimate travel distances, velocities of discharges into the receiving water are needed. Measurements of discharge velocity in these tributary channels are not available, but as a start, we modeled a semicircular cross section with a width of about 4 m for the ESPS/Emeryville North watershed based on natural channels for similarly sized watersheds in the region. This resulted in an average flow velocity of around 1.7 m/sec, assuming the discharge from a 1 year ARI rainfall occurred entirely within 3 hours, or that a 10 year ARI rainfall discharged within 6 hours. These velocities, near 2 m/sec, appear reasonable based on observed storm flow rates in other watersheds. For the Temescal Creek watershed and a hypothetical combined watershed, we assumed that the average flow velocity would be about the same, and thus scaled the channel cross sectional area proportional to total flow to yield the same linear velocities. Higher velocities will tend to erode natural channels and thus self-enlarge their cross sectional areas, so similar maximum channel velocities may be a reasonable first approximation.

In order to estimate the distance over which the exit velocity of these streams carried, we applied heuristic empirical calculations derived for turbulent jets (Cushman-Roisin 2014). Typically these calculations are applied to idealized scenarios of entry into a completely enveloping volume of the same fluid, conditions not strictly met in this case, as the flow is constrained by the air/water and air/sediment interfaces, and the discharge is freshwater, while the receiving water is saltwater or brackish. Nonetheless, these calculations can provide a rough sense of the scale over which discharged sediment might be initially carried. The maximum velocity (u_{max}) along the main discharge axis and mean velocity (u_{mean}) across at any given distance x can be estimated as a function of the jet outlet diameter, d, and the average velocity at the outlet, U:

$$u_{max}(x) = 5\ d\ U\ /\ x$$

$$u_{mean}(x) = 2.5\ d\ U\ /\ x$$

In this equation x is the distance from a virtual point outlet, which occurs 2.5 d upstream of the actual outlet. At large distances from the actual outlet, the error of ignoring this factor is small (e.g., ~2.5% at 100 diameters downstream), but at shorter distances, using the distance from the actual rather than the virtual point outlet yields very large errors (for example, at the actual outlet, using x = 0 rather than the correct x = 2.5 d yields an undefined u_{mean}, rather than the correct mean velocity of U at the actual outlet).

An integration of the estimated u_{max} over the first hour of discharge for a 1 year ARI rainfall discharged over 3 hours for Emeryville North suggests a maximum travel distance of around 500 m for an hour of flow along the main axis. With a mean velocity 50% of the maximum, the mean travel distance of the discharged mass would be about 70% of that (square root of 50%), or 350 m. The discharge jet of the combined watersheds can be estimated in two ways. If the rest of the Crescent discharge is assumed to come from Temescal Creek, with the outlet diameter scaled to yield the same maximum flow rate (~1.7 m/sec), the maximum one hour travel distance on the main axis of that discharge would be 660 m, or 470 m for the mean mass. The two channels meet near the bottom of the intertidal zone, so as a worst-case scenario, we also estimated the jet for the combined watersheds considered as a single originating discharge (with channel diameter adjusted to yield the same linear velocity at the outlet). A larger single outlet yields greater velocities at distance than numerous smaller outlets discharging the same volume, so this likely overestimates the travel distance for the ESPS/Emeryville North and Temescal discharges combined. The one-hour maximum travel distance for this hypothetical combined discharge jet was 710 m, or 500 m for the averaged mass. The zone of greatest concentration on initial discharge will be in a cone downstream of the discharge, over a width about 40% of the distance from the virtual outlet, with the highest concentrations near the central axis of the discharge. These hypothetical cones of discharge are overlaid as yellow triangles on the PMU map in Figure 3-10 for discharges from Temescal and ESPS/Emeryville North at high slack (near the MHHW line), and a hypothetical combined flow for the watersheds extending from the low slack (near the MLLW line) entry point. Because discharges may occur at random points in the tidal cycle, a hypothetical area connecting these potential deposit cones between MLLW and MHHW represent our best guess as to where the most elevated concentrations might be found.

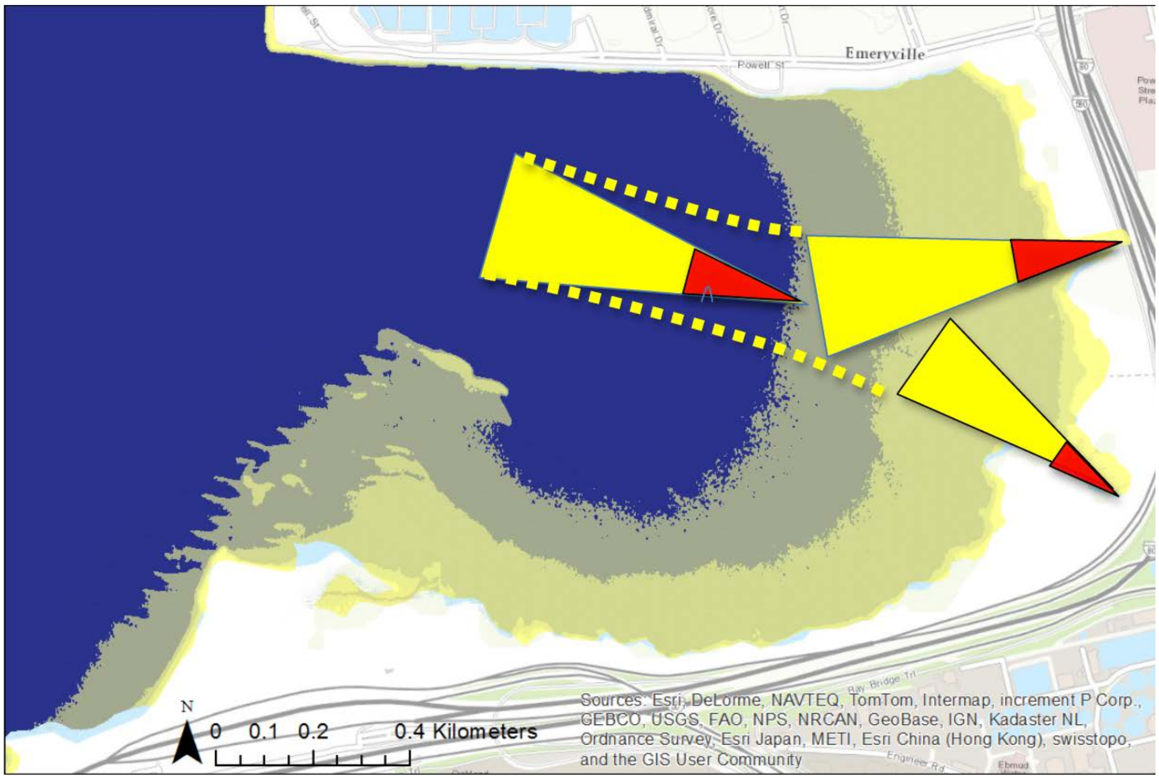

Figure 3-10. Hypothesized short-term deposition zones. Yellow triangles represent 1-hour settling areas for a combined outflow at MLLW, or Temescal and ESPS/Emeryville North separately at MHHW. Yellow dotted lines delineate approximate aggregated area assuming discharges are randomly distributed over time between these tidal elevations. Red triangles indicate fast settling (0.1 hour) areas for location. Zones connecting these areas not shown, but would generally follow along the main channels through the intertidal zone.

Similarly, the travel distance of a fast-settling fraction can be estimated from previous settling studies for the BMP project. With a settling rate of 10 m/hr or faster, only 6 minutes would be required for sediment to drop out of a 1 m water column. Calculated maximum travel distances for ESPS/Emeryville North, Temescal, and a combined discharge range from 160 to 220 m for this 1 m drop, so we would expect a sizable proportion (around 15 to 50%) of discharged PCBs to be initially found in the very near field, and several hundred meters beyond the entry point at MLLW at the furthest. These zones are marked in Figure 3-10 as red triangles. Over time, resuspension and tidal currents will tend to disperse the initial discharge deposits, but some signal of the initial deposits may remain, especially for heavier discharged sediment, particularly in areas at the upper end of the tidal range, which would be subject to resuspension and transport for a lower proportion of time. Vegetated areas such as on the eastern side of the Crescent and the southern side around the Bay Bridge toll plaza (Figure 1-1) would similarly see less reworking, as they are typically even higher in elevation (e.g., in much of the emergent marsh present in the Crescent above MHW), and the vegetation would dissipate wave energy and buffer tidal flows that might otherwise carry away contaminated sediment.

f. Monitoring recommendations

Recommendations for initial monitoring depend ultimately on the questions to be answered.

If the primary objective is to identify monitoring locations that are disproportionately influenced by recent initial discharge from the watersheds, the focus should be in the near field of discharge channels from the watersheds of interest, and particularly high in the intertidal zone where the time for resuspension is reduced. Thus for ESPS/Emeryville North, we would want to examine within the first 200 m of the various potential high and low tide discharge points, since we wouldn't necessarily know when and where the largest discharge events occurred. The point of entry at low tide is near the entry point for the Temescal watershed, so any signal would likely be diluted out by that flow, as well as being subject to resuspension and tidal transport for a greater proportion of time. Concentrations would tend to be higher near the center of the outflow, but not necessarily at the center of the flow channel itself, which may scour during high flow events. The PCBs previously measured by BPTCP at an intertidal site in the Crescent were higher than nearby open Bay ambient concentrations, consistent with expected gradients (at least in a broad sense). However, it is unknown whether concentrations there are currently as high, or whether points in transects parallel or perpendicular to the channel flow would show the gradients expected in this conceptual model.

A monitoring plan for confirming a conceptual model of initial discharge would focus on a grid or array of transects around the discharge channel, with samples near the central axis of the discharge channel at regular intervals (e.g., every ~200 m or so) from its entry points at MHW to MLW, and transects off that central axis through the intertidal zone, and then transects around the 0.1 hour and 1 hour maximum travel distances in the subtidal zone (around 200 m and 700 m, respectively). Samples collected near the end of a wet season would capture the cumulative effect of multiple storms; passive sediment traps or passive samplers would be useful for characterizing new deposition. In contrast, shallow surface sediment grabs would better reflect the combined effects of short-term environmental processes (e.g., including bioturbation). For the latter, the depth of sample analyzed would be very critical. Too deep of a sample could integrate several years' or decades' environmental processes, and thus dilute out possible signals of change. Too shallow of a grab might mainly capture only late season deposits and thus represent a net result of only late wet season resuspension and redeposition rather than a total of wet season loads and processes.

If instead the primary focus is trying to understand the ongoing and prospective environmental exposure of biosentinel species of interest, then a sampling plan should be built around the habitat utilization profile of that species, with grid or random-stratified sampling of the habitat of interest. A hybrid approach might incorporate elements from that for characterization of discharge deposits, e.g., distributed through the habitat, but at higher intensity near the discharge channels. Inevitably, there may be compromises in any combined approaches; exposure assessment may require either shallower or deeper samples, tailored to specific species. Conversely, samples optimized for detecting trends in recent discharges might not include enough or any of the legacy sediment contributing exposure, and thus under-estimate continued long-term risk from bioturbation and episodic resuspension. Sediment cores or passive sampler profiles might be able to capture both, but incur higher analytical costs (roughly proportional to the number of discrete sections analyzed).

The "right" approach for monitoring given limited resources therefore depends highly on management priorities. Plans for longer term monitoring are also highly dependent on relative priorities for different types of information. Presumably, whatever type of data is collected in the short term, similar information would be desired in the future as indicators of trend.

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4. Long-Term Fate in the PMU

a. Fate conceptual model

As mentioned in the previous section, the indicators of interest are dependent on the prioritization among various questions to be answered. For biotic exposure, we may be interested the entire zone of sediment utilized by a species. For characterizing effects of watershed management, we may be most interested in characterizing recent sediments, occurring after actions have been taken. Addressing different objectives may require taking different types of samples, or recognizing the limitations and compromises of approaches that attempt to combine objectives.

i. Simple box model

A recent fate model developed by Dr. Frank Gobas' group at Trent University models the exposure and bioaccumulation of persistent organic pollutants (POPs) by organisms exposed to a heterogeneous mix of contamination. This model is similar to that group's previous fugacity-based exposure models, with the main change being the ability to explicitly model exposure from different zones, rather than derive a single spatially averaged exposure. Conceptually the Crescent can be broken up into three zones, the vegetated intertidal marsh, the unvegetated intertidal mudflat, and the always-submerged subtidal zone. Some species such as small prey fish may occupy all these habitats at different times (e.g., when the water depth is appropriate). Others may be more restricted to one or two of these zones, or even just one portion of one of the zones (e.g., the portion of mudflat below MLLW for organisms preferring or requiring cooler and constantly submerged conditions). The Gobas multi-compartment model currently only considers the biological exposure and fate aspects of POP fate, so the environmental concentrations of the contaminants of interest are required input parameters for each of the compartments. Gobas' group is working to develop a model of abiotic fate and transport to link with the biotic model, but at present we need to use empirical data or separately devise a simple model of contaminant fate. A significant advantage of a fate model is that it allows forecasting of future environmental concentrations and evaluation of different management scenarios.

ii. Congeners and sub-habitats considered

Currently there are few data on environmental concentrations of PCBs in the Crescent and there is a need to estimate long-term rates of change in environmental concentrations. Therefore, we consider a simple one-box fate model using input parameters for the Crescent and a possible range of starting ambient sediment PCB concentrations in the Crescent. Following the approach used in the whole-Bay one-box model of PCB fate (Davis 2004) we first consider the fate of PCB 118, while acknowledging the uncertainty bands of having selected only one representative congener. Fate based on the physico-chemical properties of select lighter and heavier congeners is later examined. Ultimately, each of the congeners could be considered and modeled separately, which would likely illustrate slightly different evolution of the fate profiles for the various congeners. However, that is a bigger effort to be considered for the future (e.g., to model fate of specific dioxin-like PCBs, or to calibrate to observed congener profiles in discharges versus the ambient sediment in the Crescent).

Another likely even larger challenge is to develop fate models for the different sub-habitats within the Crescent. Transport of sediments and contaminants between these habitat compartments is not continuous, so devising schemes for representing and estimating rates for these transfers (even on a pseudo-continuous time-averaged basis) presents a significant challenge. The mass budget presented here therefore represents an initial scoping effort to evaluate the likely range of responses in the environment that might be observed due to loading changes, for different assumptions of critical environmental parameters.

b. Mass budget

A conceptual illustration of the components in the simple mass budget model is shown in Figure 4-1.

Currently, one very large uncertainty is the initial inventory of PCBs in the Crescent. One large element of that uncertainty is the limited availability of sediment PCB data for the area. Currently we have PCB data only for one site within and a few nearby sites outside of the Crescent PMU. The site in the Crescent (possibly higher than average since it was in the intertidal zone) was 86 ng/g. Nearby sites range from around 10 ng/g near the end of Berkeley Pier, to 20 ng/g in Oakland Harbor just to the south, to around 36 ng/g at Emeryville Marina. We therefore considered concentrations between 10 ng/g and 50 ng/g as a possible range for the Crescent average to use in a one-box fate model.

The second large element of uncertainty is the depth of the "active" sediment layer, which impacts the calculated inventory. In the Bay one-box fate model, an active sediment layer depth of 15 cm was used. We therefore used 15 cm as our baseline assumption here, but considered alternative depths of 5, 10, 20, and 25 cm. Table 4-1 presents the range of PCB mass inventories for assumptions covering this range of active layer depths and average PCB concentrations. Since the estimated inventory is a product of the sediment volume (proportional to mixed layer depth) and sediment concentration, the calculated initial inventory is linearly proportional to both these parameters. Given the concentrations at nearby Emeryville Marina (36 ng/g) and Oakland Harbor (20 ng/g), a base case assumption in that range combined with a 15 cm mixed layer used in the Bay model may be a reasonable starting point. Other underlying assumptions and parameters used for this simple model will be discussed in the following section.

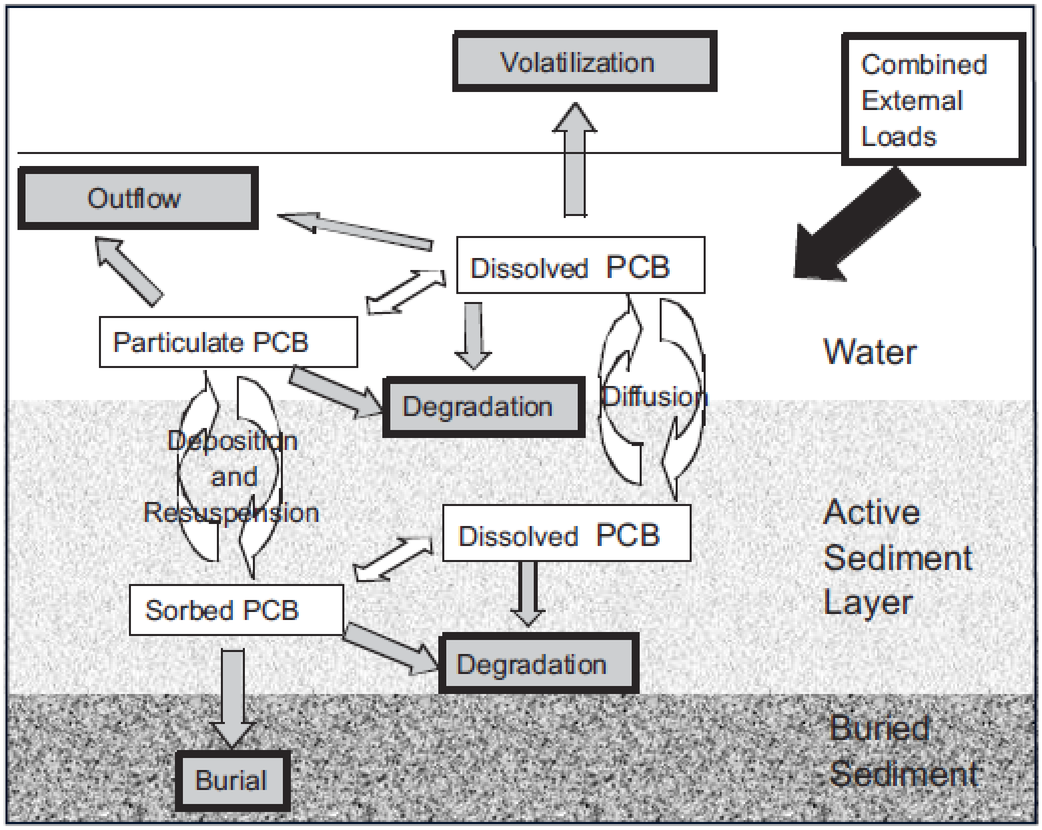

Figure 4-1. PCB Fate Conceptual Model (from Davis, 2004)

	10ng/g	20ng/g	30ng/g	40ng/g	50ng/g
5cm	0.4	0.9	1.3	1.8	2.2
10cm	0.9	1.8	2.7	3.6	4.5
15cm	1.3	2.7	4.0	5.4	6.7
20cm	1.8	3.6	5.4	7.2	8.9
25cm	2.2	4.5	6.7	8.9	11.2

Table 4-1. Mass budget starting sediment PCB mass (kg), varying assumptions of initial PCB concentration and mixed layer depth

1. Inputs

Inputs of PCBs to the Crescent originate either from the surrounding watersheds, or from adjacent areas in Central Bay. Section 2 described the process for calculating average annual PCB loads from these watersheds, using long-term precipitation records, runoff coefficients for various land uses, and a flow-proportional (i.e., constant water concentration) assumption, yielding 214 g per year. For our base case scenario we assume that this entire annual load remains and is incorporated into the Crescent inventory. For one-year ARI events and smaller, which account for the vast majority of the overall load, this complete retention assumption may be reasonable, as the previous discussion on discharge jet extents suggest the discharged volume would remain largely in the Crescent, even if discharged at MLLW. A reasonable alternative scenario is to assume that the portion that settles at rates <1 m/hr in a quiescent lab scenario will not settle at all in the ambient environment with tidal currents, wind waves, and other forces tending to keep particles in suspension. With 30% to 70% of PCBs slowly or not settling in a lab setting, a 50% reduction in watershed loads from the base case can illustrate the impact of reduced initial retention on long term fate. Impacts of lowered loads from lowering estimated retention of initial loads will be examined in the discussion of the influence of external loads on mass budget model outputs later.

RMP station BC10 is nearby, and may represent a reasonable long-term record of ambient Bay water concentrations exchanging with the Crescent. Total water PCBs at BC10 have averaged around 200 pg/L in samples collected since 2006. Due to the shallowness of the Crescent, its tidal prism is nearly 5/6 of its total volume at MHHW. Although some of the water returning on each flood tide was exported on the previous ebb tide, as described previously in Section 3 on preliminary hydrodynamic modeling, a majority of water entering is from the adjacent open Bay. Combining approximately twice daily tidal volumes with the adjacent BC10 water concentrations, an estimated 1.2 g of PCBs is supplied to the Crescent per day, about double the daily averaged loading rate from the watersheds. Using the full tidal prism of the Crescent likely overestimates the tidal exchange somewhat. Although the majority of the Crescent empties on the ebb tide, about 30% of that returns on the subsequent flood, so the “new” water exchanged is effectively about 70% of the tidal prism. The watershed loads are episodic and associated primarily with storm events, so on any given day during the rainy season, watershed inputs may dominate, but in considering multi-decadal fate, the long-term average load is more important than capturing any single event.

2. Internal processes

Important internal processes affecting the long-term fate of contaminants include the mixing and dispersion of bed sediments, and the settling and resuspension of sediments in the water column. For the purposes of the one-box model as an integrative framework for assessing available data and gaps and uncertainties, the Crescent is treated as a single homogenous compartment, but we recognize that persistent heterogeneous contaminant distributions at other sites illustrate this is not likely the actual case. The one-box model treats the water column and mixed sediment layer each as instantaneously (within the annually-averaged parameters in the model) uniform compartments. Overall this tends to accelerate likely changes; new contaminant loads are instantly spread, and exports in the water column are based on compartment-averaged concentrations rather than on integrated flux of concentrations at the boundary. Even in the case of reduced loads, the simply modeled (instantly mixing) system as a whole overall responds more quickly than in the real world. Newly deposited cleaner sediment may persist on the surface in real life, creating a faster short-term response in the sub-habitat for surface-feeding biota, but conversely resulting in slower response to the final steady state for deeper feeding organisms, and for the overall contaminant inventory. More realistic modeling of bioturbation and resuspension would transport deeper contaminated sediments to the surface only slowly, reducing their potential rate of eventual removal from the margin area. Only in the case of rapid burial would slow mixing improve the recovery rate; the deepest and presumably more contaminated sediment would be buried first and be pushed out of the zone of potential mixing. A more mechanistic handling of processes would require a multi-compartment hydrodynamic model, and a multi-compartment (both laterally and vertically) sediment fate model, a much larger effort than possible with the available data and for the scope of this conceptual model study. However, we can characterize the results of our simplifying assumptions, and how they may mis-estimate the actual environmental processes.

Although this simple model does not explicitly describe a bed sediment mixing rate, a key parameter for simulating these processes is the mixed sediment layer depth. The selection of the mixed sediment depth effectively defines the contaminant inventory and inertia of the system. A large mixed layer depth defines a large sediment mass, so new contaminant inputs are effectively diluted over a larger mass and thus averaged concentrations change slowly. Similarly, effects of decreases in loads occur more slowly, as the selection of a large mixed layer depth includes a large inventory of contamination that is presumed to continue to interact with the water column and resident biota in the long term. Conversely, a small mixed layer depth implies and small inventory and little inertia. Changes are presumed to be manifested relatively rapidly. A good selection of mixed layer depth can provide an appropriate approximation of the average system response for an indicator of interest at a whole compartment level (e.g., spatially averaged concentration, or wide scale exposure for a biosentinel species), but effects of lateral heterogeneity cannot be captured without explicit multi-compartment modeling. The whole bay model mixed sediment layer depth of 15 cm was selected as a reasonable starting point based on burrowing depths, radiotracer penetration, and other data, while recognizing that this key parameter is in reality spatially heterogeneous. The applicability of the same value to shallow margin areas is particularly uncertain, as the resident bioturbating species may differ from those in the open bay. The depth of wave-driven sediment mixing also differs from that in the open Bay, perhaps episodically much larger, due to the shallowness of much of the area. Localized benthic surveys, and tracer horizon studies would provide some better information on sediment mixing in the area.

Suspended solids settling and sediment resuspension are major pathways for transfer of PCBs between the water column and bed sediment. Key parameters affecting suspended solids settling are the average water depth and the average settling rate of solids. A settling rate of 1.0 m d^{-1} was used as in the whole bay model, and with an average depth of 2 m for the Crescent, about one quarter the suspended solids are settled out each tidal cycle, and the PCBs in the particulate water column fraction are transferred to the sediment. However, this rate of settling would result in rapid net accretion of sediment within the Crescent, so an offsetting resuspension rate is calculated as the difference between settling and net burial. If we presume no net burial, the settling and resuspension rates are equal. The flux of PCBs from the sediment to the water is calculated as the sediment resuspension flux multiplied by the averaged sediment concentration. A key parameter in both these rates (especially in the resuspension flux) is the suspended solids concentration. Due to the large tidal exchange for the Crescent, with the majority of its volume exiting on each tide, the influence of this parameter on net PCB export is very large (approximately linearly proportional)

3. Losses

In the whole Bay box model the base case assumption was that the burial rate was negligible or zero. Here we make the same assumption, but other assumptions can be evaluated simply based on the ratio of burial rate in cm per year relative to the mixed layer depth. For example, a 3 mm per year burial rate (approximately keeping up with sea level rise) on a 15 cm mixed sediment layer represents a 2% loss of sediment PCBs per year (the addition of 3 mm on top from the water column solids in this scenario may increase or decrease net sediment inventory, depending on initial concentrations).

Volatilization is modeled as exchange from the water column to the air. For the Crescent, due to the steep edge of much of the armored shoreline, the difference in area between MHHW and MSL is only 2%. However the exposed area at MLLW is nearly 40% of the total area, so further refinements might be to consider direct volatilization from exposed sediment or a very thin surface porewater layer. However volatilization losses only account for less than 1% loss of PCBs from the Crescent. Volatilization rates would have to increase substantially; for the current model, at the extreme, assuming that all PCBs in the Crescent were the relatively volatile congener PCB 18 still only resulted in loss rates of about 11% of PCB mass each year.

Water column and sediment degradation of PCBs is also presumed to be relatively slow; a large part of the problem with PCBs is their persistence in the environment. As in the whole Bay mass budget, we used a default half-life of 56 years. This resulted in around 1% loss of PCBs per year. Adjustments to the assumed half-life in sediment proportionally increased degradation loss rates; assuming an 11-year half-life increased degradation losses to around 5% per year.

By far, the dominant factors in the PCB mass budget for the Crescent are the assumptions that directly impact advective (primarily tidal) export. With around 5/6 of the volume of the Crescent exiting and entering on each tide, and about 70%

of the volume at high slack being water that was not in the Crescent on the previous high, any PCBs remaining in the water column over a tidal cycle will be rapidly lost. A critical unknown is the average water column PCB concentration of the waters that exit the Crescent on each tide and do not return. Due to the much larger spatial extent and tidal volume of San Francisco Bay relative to its tidal prism, rather than using a whole Bay average concentration to estimate export as would be the expected case for a pure one-box model, an adjustment using the near exit station average concentration (i.e., presuming only waters near the exit leave the bay on any given tide) was made for the previous model. In contrast, for the Crescent, 70% of the total volume leaves and does not return in the short term. However, even for this small area with a larger tidal prism relative to its volume, some adjustments are needed to account for likely spatial gradients.

Because we do not have any water column PCB concentrations for the Crescent, as a first-order estimate, we could assume that the steady state water column concentrations were effectively the suspended sediment concentrations multiplied by the sediment PCB concentrations. However, with 70% of the water on each high tide not originally within the Crescent, this assumption would likely be a large overestimate. We therefore adjusted that initial estimate, assuming that the 16% (one-sixth) of water remaining at low tides contained solids in steady state with those in the Crescent, with the remaining volume containing a linear blend with waters outside of the Crescent, near the long-term average concentration at RMP station BC10 (around 200 pg/L total PCBs). The model in the long term is not sensitive to the assumed initial water column concentration however, as the water inventory rapidly adjusts in response to the combination of watershed loads, resuspension from bed sediment, and flux with the open Bay.

The net export is adjusted similarly to the calculation of initial concentration. The 16% of volume never leaving the Crescent is presumed in local steady state, and the remaining 84% of volume leaving ranging linearly from 100% local Crescent to 100% open Bay (BC10) water. The eastern-most waters, following the leading edge of the rising tide, have the longest duration of exposure, but much of that volume does not or just barely exits the Crescent at low tide, so the net export of that eastern fraction of waters may be near zero. The transported water generally follows a last-in-first-out (LIFO) pattern; the last waters to enter the area from the open Bay are those that first leave and thus had the least time to equilibrate or exchange with local sediments (as well as having a higher tidal depth, thus actually less likely to transmit wave energy to the bottom). Conversely, in addition to the 16% of waters that never leave, about 14% of the volume (that portion next most locally-influenced) immediately returns, so the permanently exported volume ranges from ~0% to 83% of the steady state concentration. Assuming linear mixing, the average is the midpoint of the range, so we therefore adjusted the net tidal export to be 42% (=83%/2) of the steady state value.

Another parameter to which the modeled export is extremely sensitive is the assumed SSC. Using the value from the whole Bay model (8.5×10^{-5} kg/L), even adjusting for the assumed mixing between "new" and returning water PCB concentrations, we obtain an annual tidal export equivalent to around 1/3 of the initial sediment PCB inventory. At steady state, that exported mass is offset by import from the open bay, combined with loading from surrounding watersheds. Based on the one-box model to be discussed in the following section, the apparent half-response time is several years, but any changes in loads are relatively rapidly manifested. Given the persistence of highly contaminated areas for other sites, such rapid turnover is highly unlikely, or would require high ongoing loading rates to maintain locally elevated concentrations. Adjusting the suspended sediment concentration (SSC) up or down increases and decreases the export rate respectively, so clearly a better quantification of the suspended sediment pool available for tidal export is needed to generate accurate fate scenarios for PCBs in the Crescent. In addition to better quantification of local suspended sediments in the Crescent, a more detailed model of sediment resuspension across the intertidal zone may be needed to estimate the proportion of sediments that are resuspended versus imported from outside the Crescent on the flood tide. An improved model would account for the depth and exposure time for different parcels of water entering and exiting over a tidal cycle to calculate the percentage of suspended sediments originating from local bed sediments, and ideally link to modeled or empirically mapped sediment PCB concentrations for the area. Such improvements would require either explicit modeling of different zones within the Crescent (i.e., a multi-box model), or a simplified (e.g., spatially and temporally averaged) approximation of these complex processes.

iii. Forecasts

Figure 4-2 shows recovery trajectories for different starting sediment concentration scenarios. In this simple model, annual loads and fate processes are assumed to be interannually consistent. This is seldom the case, but even so, the model can illustrate the long-term temporally averaged fate (e.g., actual concentrations and loads each year would vary around the modeled steady state). Based on ambient concentrations from nearby stations of around 20 ng/g (Oakland Harbor) and 36 ng/g (Emeryville Marina), an initial concentration of around 30 ng/g was expected to represent a reasonable current steady state. Although the initial inventories of PCBs varied with the starting sediment concentration, the half-response times and the final steady state concentrations were identical, as would be expected. The current mass budget model results suggest continued loading at the present estimated level would support ambient concentrations in the Crescent near 20 ng/g PCBs (the scenario where the final steady state inventory is nearest the initial mass). However, there are considerable uncertainties in the degree of water column exchange with the open Bay, as well as in exchange with bed sediment, extremely important parameters for the model in this area given its shallow depth, with the tidal prism constituting the majority of its total volume. The Crescent was sampled in the recent survey of margin habitats, but these samples have not yet been analyzed for PCBs due to concerns about inter-laboratory comparability. Results from these samples (one mid-intertidal, one nearly in the subtidal zone) will be important data for ground-truth validating some of the parameters and other assumptions of the model. Given the dynamic changes in depth and volume of the Crescent over the course of a tidal cycle, application of a one-box fate model may be insufficient, and various processes may need to be explicitly mechanistically modeled or otherwise approximated through additional adjustment factors (e.g., like the adjustment for LIFO tidal exchange assuming a linear gradient attempted here).

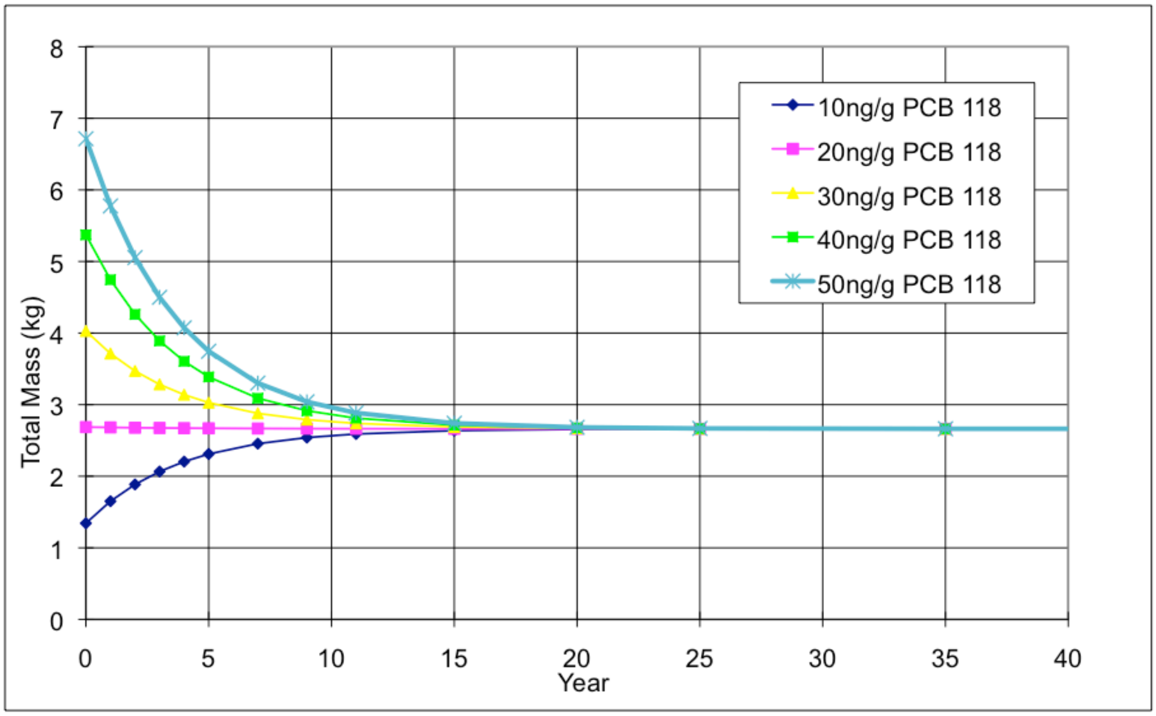

Figure 4-2. Recovery trajectories from differing starting concentrations, constant watershed and Bay loading, other parameters from open Bay one-box PCB model (15 cm mixed layer, Bay SSC, 1 m/day settling, no burial). Around 20 ng/g sediment concentration would be supported at steady state with current watershed and Bay loads.

Figure 4-3 shows recovery trajectories for different watershed loading rates, assuming that initial sediment concentrations average 20 ng/g. In these scenarios, the half-response times remain the same, but the final steady state masses are linearly proportional to watershed loads added to the no (0x) load case, where the only new PCBs are contributed by exchange with the open Bay. The current (1x) load scenario represents something of a worst-case assumption for current estimated loads, with 100% of the watershed load incorporated into the inventory. A reasonable alternative scenario is that about half of the total load is dissolved or not easily settled (an assumption about midway between the minimum and maximum proportion settling at <1m/hr in lab experiments), and assuming that portion of watershed load is effectively lost from the Crescent after one or more tidal cycles.

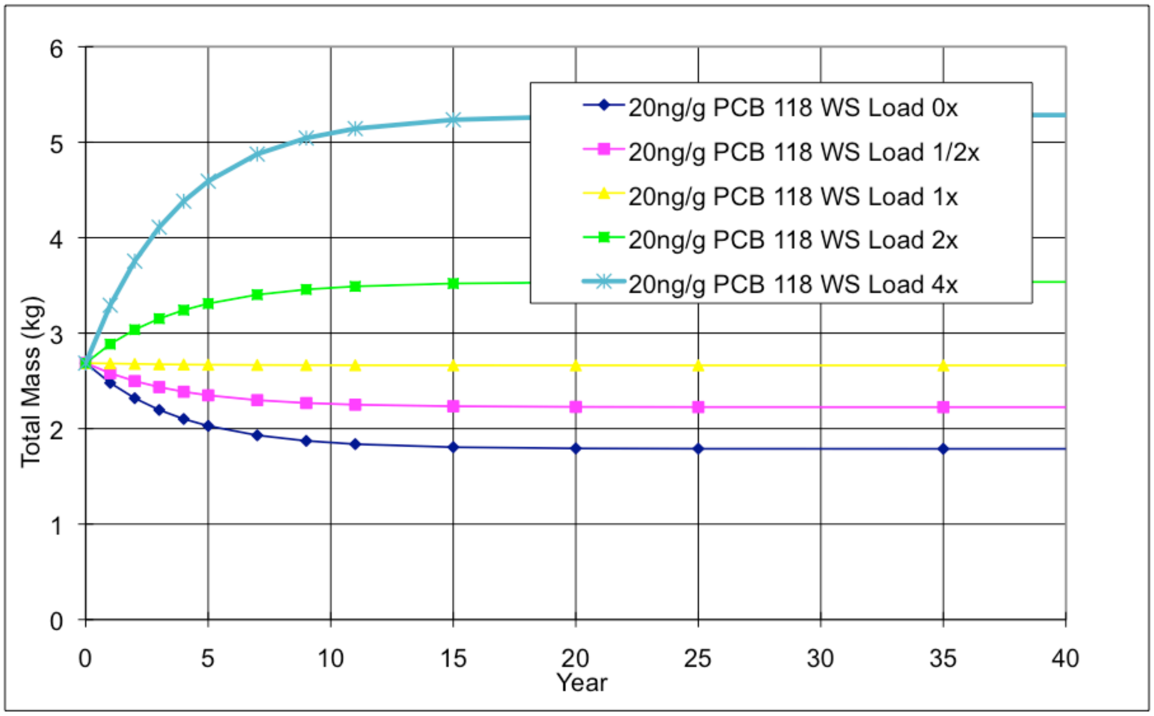

Figure 4-3. Trajectories with 20 ng/g starting concentrations and differing watershed loads; other parameters the same as in Figure 4-2. In the base (1x) load case, the watershed load is half the tidal load from the Bay.

1. Uncertainty of estimates

Like the previous whole Bay one-box model, the response of the modeled ecosystem is highly dependent on various modeled parameters. However, given the shallowness and large tidal prism relative to volume for the Crescent, unlike the whole Bay model where the starting inventory and net sediment processes strongly affected the response and long-term trajectory, here the most influential parameters are those affecting net loading and export. Although the initial sediment concentration will affect the inventory in the short term, the base case model (Figure 4-2) for all starting bed sediment concentrations at 10 years is within 10% of the final steady state inventory supported by current levels of loading. The model responds similarly quickly to increases or decreases in loads (Figure 4-3). As would be expected, given the large tidal excursion relative to total volume, adjustments to parameters affecting SSC and tidal export (i.e., the calculated average concentration adjustment factor for exported water) are highly influential, leading to nearly directly proportionally higher and lower final steady states, for lower (lower SSC, or lower PCB concentration relative to local sediment) and higher (higher SSC or higher PCB concentration relative to local sediment) export rates (Figure 4-4).

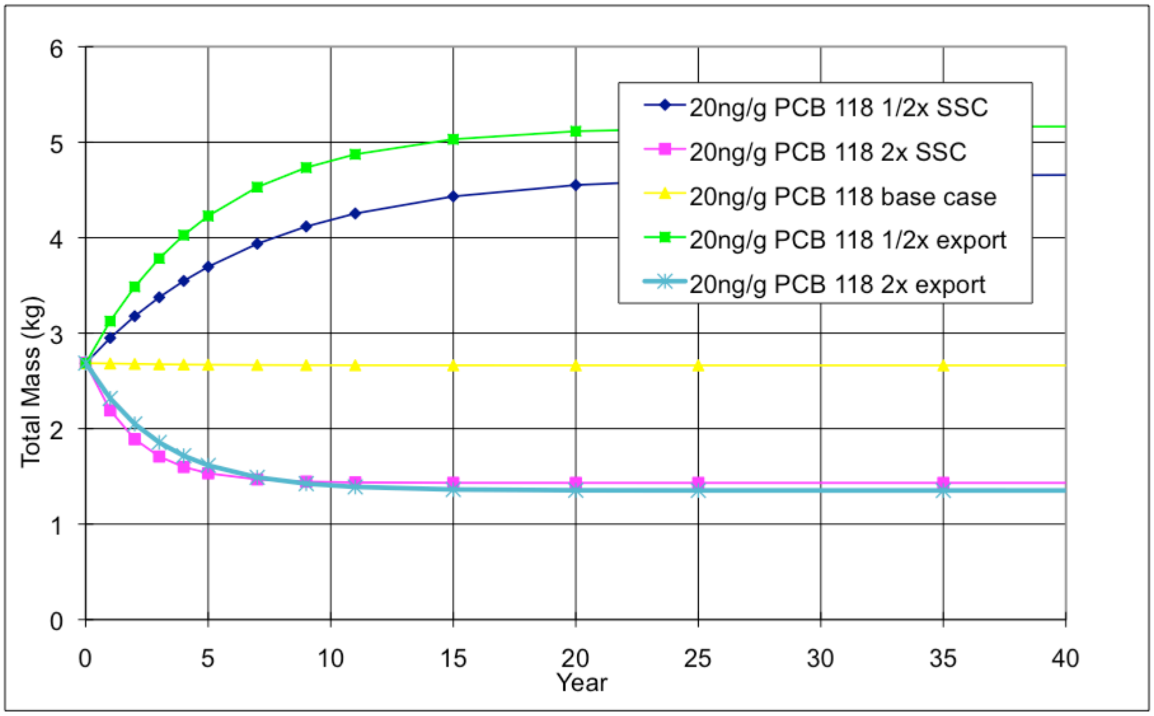

Figure 4-4. Trajectories under base case loads, with different SSC and tidal export parameterization

Factors affecting the sediment compartment fate such as burial and erosion rates, and degradation rates, had only minor impact on overall fate, even when starting with higher sediment concentrations than would be supported by estimated ongoing loads (Figure 4-5). The differences among scenarios with burial and erosion (around average sea level rise rate, 2mm/year) and with two-fold higher and lower sediment and water degradation rates had very minor impacts on the trajectory and long-term steady state inventory. Similarly, increasing the mixed sediment layer thickness, even when compounded by higher initial sediment concentration (30 ng/g) than would be supported by current ongoing loads, shows only a modest effect (Figure 4-6) of increasing the response time. The final inventories are directly affected by including larger volumes of sediment, but the final concentrations and masses relative to initial values are similar albeit slightly different (due to differing effective residence times in the mixed layer, thicker layers will have on average older and thus more degraded sediment for a given exchange rate with the water column).

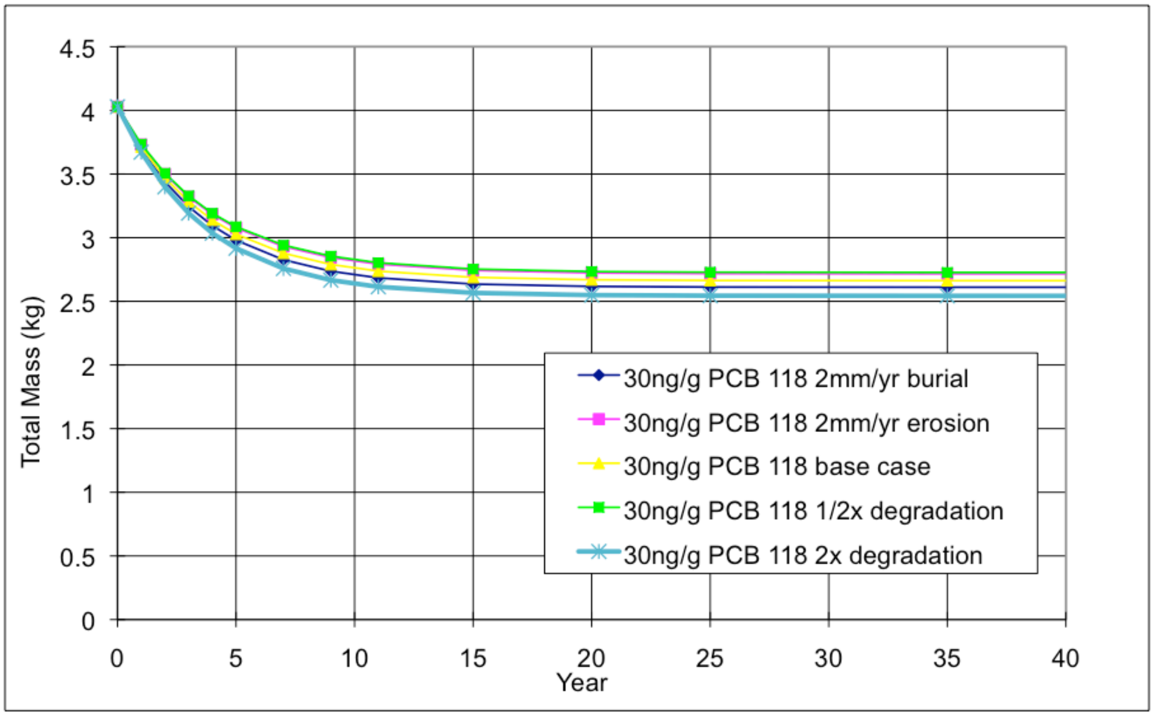

Figure 4-5. Trajectories under base case loads, with different burial and degradation rate parameterization. Initial concentration raised slightly over usual base case to increase relative importance of degradation rate.

The selection of the congener to represent PCBs in general also had a moderately large influence. Ideally, rather than selecting a single congener to represent all PCBs, individual congener fates would be tracked separately. However, that would require a much higher level of effort. Given the high degree of uncertainty in other critical parameters, at this point, separate modeling of congeners is premature. However, the results of changing the physico-chemical properties to match those of lighter and heavier congeners (Figure 4-7) illustrates the large influence of water column fate characteristics. For lighter congeners such as PCB 18 and 66, their higher solubilities and volatilities lead to much greater outflow loss rates and lower final steady states for a given loading rate than the base PCB 118 case. Conversely, PCB 153 and 194 show higher final inventories. Separate tracking of individual PCBs may eventually be useful however; if consistent profiles for averaged loads can be established, we may be able to better calibrate or validate various modeled parameters by differentiating processes that would be more congener-specific (e.g., dissolution) versus less (e.g., resuspension).

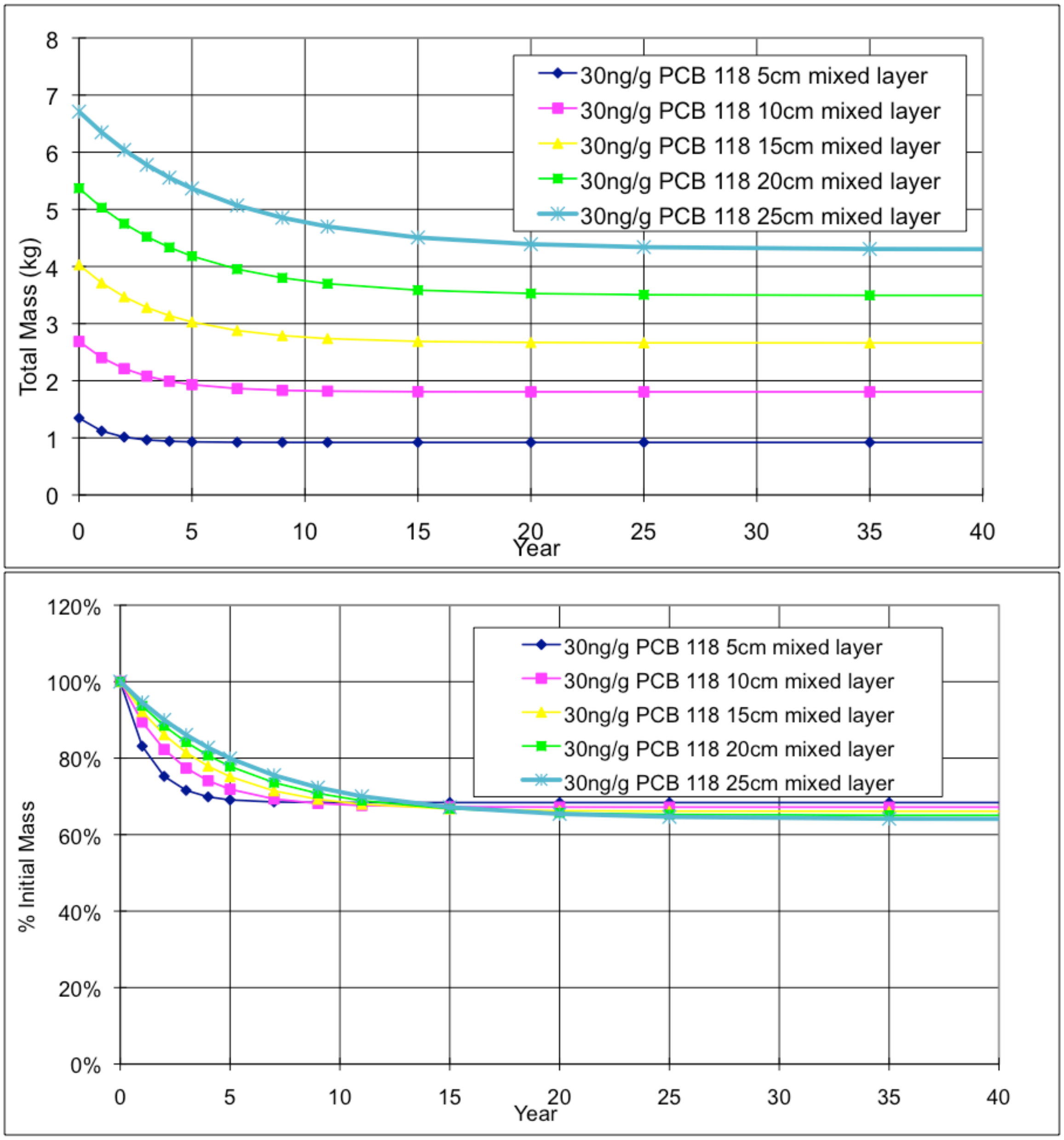

Figure 4-6. Trajectories under base case loads using different mixed layer thickness in model, shown as masses and as percentages of initial masses. Initial sediment concentration also raised (to better show change in mass, as 20 ng/g base case is already near steady state and would show little separation among mixed layer depths)

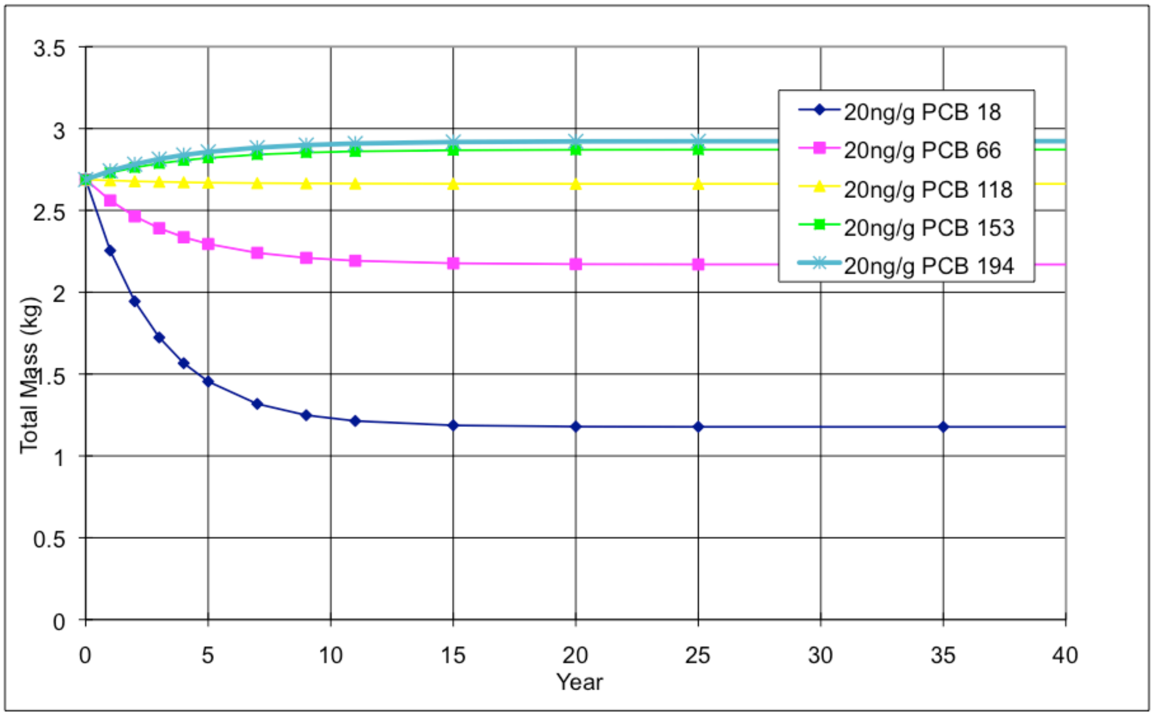

Figure 4-7. Trajectories for different congeners, base case loads. Differences are in solubility and volatility (degradation rates unchanged among congeners)

2. Effect of sea level rise

Sea level rise is not explicitly captured in the model, but may affect various parameters influencing fate. For example, sea level rising against a shoreline armored to protect property and transportation infrastructure will tend to drown and shrink any existing vegetated intertidal zones, extend the period that remaining intertidal zones are submerged, and thus allow greater resuspension and export. Much of the eventual fate of the Crescent will depend on whether there is sufficient sediment supply to keep up with sea level rise, but there is no scenario currently envisioned where the elevation would accrete faster than sea level rise, so retention of contaminants is most likely to remain the same or decrease in future scenarios.

c. Study recommendations

As mentioned previously in the discussion on initial retention of discharges, the distribution of sediment contamination within the Crescent is a critical data gap that should be filled as soon as possible, both for characterizing fate as well as evaluating the current degree of contamination within the Crescent (which over time also can be used to evaluate any trend or trajectory). A methodical survey of contamination within the Crescent will be useful for multiple purposes, helping to highlight likely weaknesses of a simple one-box approach and whether or how those weaknesses can be addressed, whether through additional adjustment factors (a relatively simple approach) or more explicit multi-compartment models (more complex and likely even more data-intensive). Samples collected under different design schemes (e.g., transects, grids, or randomly distributed within strata) can perhaps be used for multiple purposes, but as mentioned before, attention should be paid to the compromises inherent in using sample data collected from schemes not designed for the specific purposes to which they are applied.

A multi-box mass budget separately tracking vegetated wetlands, intertidal, and subtidal zones would represent one step up in level of complexity. In that application, it would become even more critical to characterize near-field deposition zones, and thus to establish discharge velocities and entry locations for various storm sizes and tidal stages. Similarly, finer scale tracking of sediment resuspension and transport would be needed, further amplifying the uncertainties and data needs for small-scale characterization of various parameters. At that scale a simple mass budget box model might not be practical; in calculating corrections for averaged parameters across a gradient of conditions, the complexity and effort required starts to approach that needed for generating and running a mechanistic model.

The utility or need for more complex models therefore is a critical question. The simple one box model highlighted some critical weaknesses and challenges of extending the box model framework to a smaller and more heterogeneous environment. Nonetheless, it served to highlight some major differences with the whole Bay scenario, namely the greater influence of ongoing loads on both the short-term and long-term fate. A more complex model of contaminant distributions would be useful in populating and applying a multi-compartment bioaccumulation model for example, but a question would be whether explicit modeling of fate is needed, or whether simpler approaches (e.g., bounding best and worst case assumptions) could also provide the information needed to make decisions.

Although collection of cores or other means of evaluating the vertical distribution of contaminants may be useful for validating assumptions about mixed sediment layer depth, the one-box model currently suggests relative insensitivity to these assumptions. Cores may still be useful however if there are uncertainties about or concerns about multiple species in the food web. For example, both surface deposit feeders and burrowing benthic organisms may be important components of diet for a biosentinel species, so characterization of vertical contaminant distributions can provide exposure information for both, rather than analyzing single composites too shallow for one species or too deep for another. Cores collected in less-mixed vegetated or higher elevation intertidal zones may also be useful markers of progress, even if only representing a tiny portion of overall area in the Crescent and thus not necessarily tightly linked to biological indicators of impairment. This would at least provide a measure of directional temporal trends, even if it does not provide a complete measure of continued ongoing risk. Short of active sediment removal or addition, relatively little can be done to alter the long-term residence time of contaminated sediments, so such a narrower view of trends (i.e., essentially focusing on changing long-term loads) can provide a less pessimistic view.

If biological monitoring is similarly focused on surface-feeding organisms, an analogous shallow sediment model may be useful. The current one-box model may provide acceptable estimates of long-term steady state fate, but will tend to smooth out all responses, diluting out short-term surface variations, and accelerating achievement of a final steady state. However, an approach centered around a surface sediment budget would de facto require a multi-box sediment model; transport past the 0.5 cm or 1 cm sediment horizon for example would not likely be "buried" in any real sense on a multi-decadal scale, so some estimate of transport of deeper sediment and contaminants back into the surface sediment compartment would be needed. Even if sediment transport across the interface with deeper sediment is not explicitly mechanistically modeled, separate tracking of the deeper layer and transfers of contaminant to and from the surface layer would be needed to not ignore the ongoing risk from legacy contamination. Again, the utility of different types of information depends critically on the questions to be answered, so differentiation of critically-needed versus intellectually interesting information is needed given limited resources.

References

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5. Bioaccumulation

a. Background and General Concepts

PCB exposure in Bay species at higher trophic levels occurs primarily through the diet. An understanding of biota life histories (diet, feeding strategy, movement, and lifespan) and the structure of the food web is therefore essential to understanding the current and future influence of tributary PCB loads on impairment of beneficial uses in the Crescent.

There appears to be a complete lack of data on PCB bioaccumulation from this area, and little information on the occurrence of species of greatest interest. However, a tentative and rudimentary picture of the food web can be constructed based on the limited data that are available, supplemented by data from nearby areas (Figure 5-1).

RMP prey fish sampling established Mississippi silverside (*Menidia audens*) and topsmelt (*Atherinops affinis*) as valuable indicator species for evaluating spatial patterns of mercury and PCB contamination (Greenfield and Allen 2013, Greenfield et al. 2013a,b). The sampling effort targeting these two species provided thorough coverage of the Bay, with topsmelt occurring more frequently at sites in Central Bay (Figures 5-2 and 5-3). Given budget constraints, PCBs were only measured at a subset of the total number of prey fish stations sampled (Figure 5-4). Even with this limited dataset, however, Greenfield and Allen (2013) were able to establish a correlation between PCB concentrations in silverside and topsmelt and concentrations at nearby RMP sediment sampling locations (Figure 5-5). These biosentinel species can therefore be linked, via sediment, to PCB exports from local watersheds.

RMP prey fish sampling did obtain samples in the Emeryville Crescent PMU - in fact, both silverside and topsmelt were both collected at the point where the West Oakland watershed drains pours into the PMU (Figures 5-2 and 5-3). PCBs, unfortunately, were not measured in these samples. However, the presence of these species in the PMU at the specific location of greatest interest is critically important in regard to developing a PCB monitoring strategy for this PMU. Silverside and topsmelt are important prey items for piscivorous fish and bird species throughout the Bay, such as striped bass (Moyle 2002), Forster's Tern (Ackerman et al. 2014), and Least Tern (Elliot et al. 2007). Based on their presence in the Crescent, they can be assumed to play a similar central role in the Crescent food web (Figure 5-1). Diet studies in the Bay margins have found that these two species have similar diets (discussed in more detail below) dominated by epibenthic invertebrates that feed on surface sediment and filter feed.

Shiner surfperch are the most important biosentinel for PCB contamination in the Bay, due to their explicit role as an indicator species for the PCB TMDL and

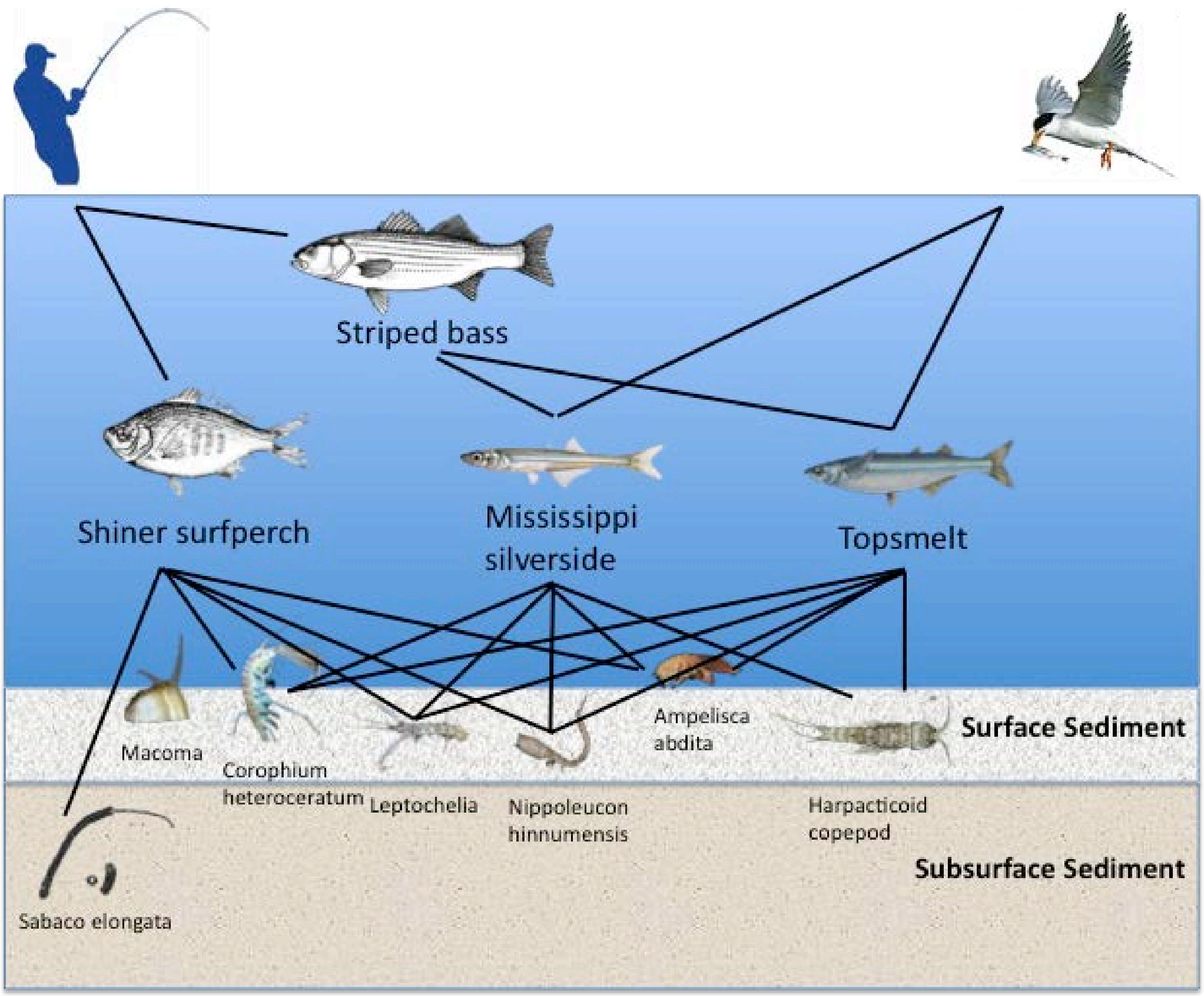


Figure 5-1. Schematic of the Emeryville Crescent food web for species of interest.

Figure 5-2. Locations where Mississippi silverside were collected in RMP prey fish sampling: a) whole Bay and b) enlarged view of Central Bay.

Figure 5-3. Locations where topsmelt were collected in RMP prey fish sampling: a) whole Bay and b) enlarged view of Central Bay.

Figure 5-4. PCB concentrations (sum of 40 congeners, ng/g wet weight) measured in a) Mississippi silverside and b) topsmelt in RMP prey fish sampling.

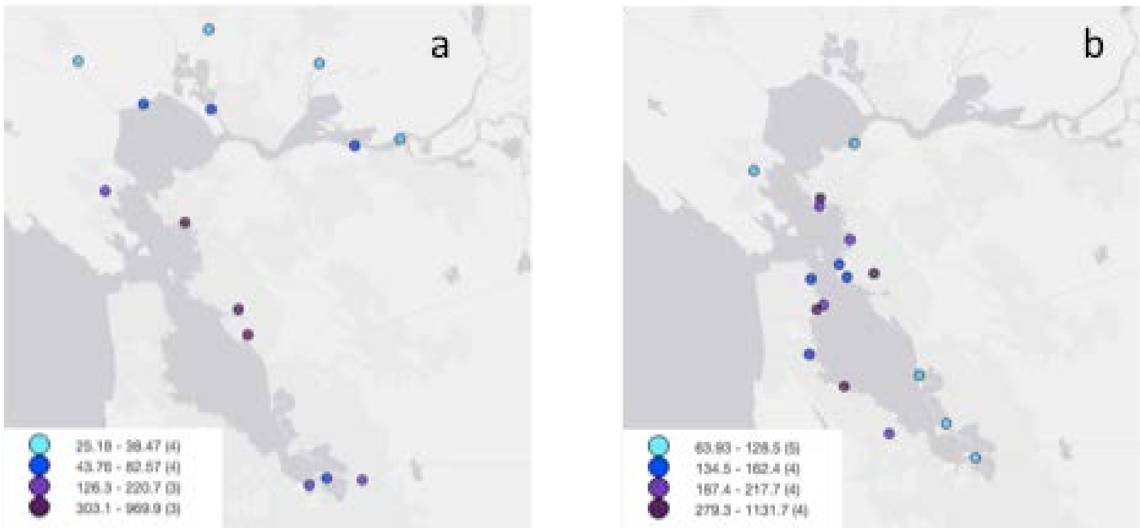
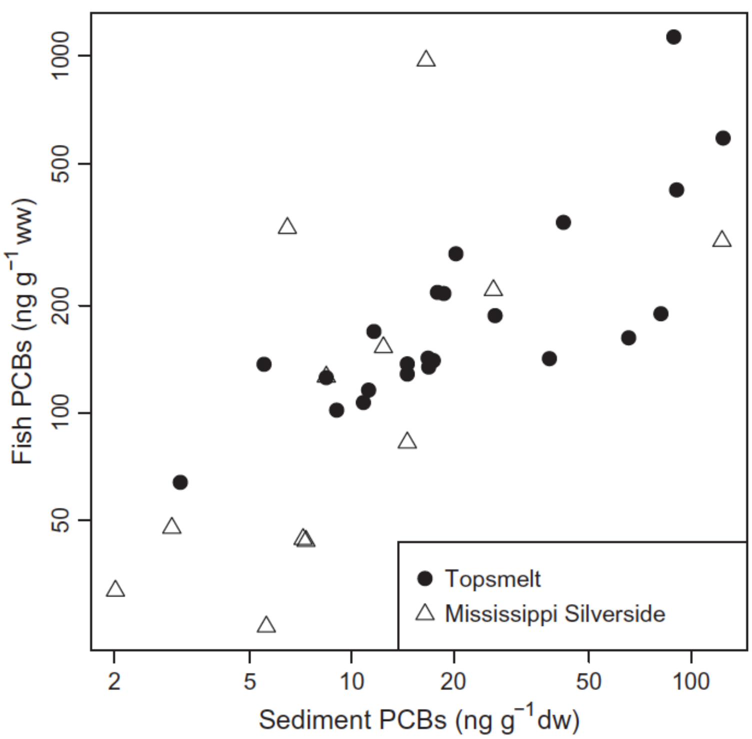


Figure 5-5. Sediment versus prey fish PCB concentrations (sum of 40 congeners). From Greenfield and Allen (2013).



the no-consumption advisory issued by OEHHA for surfperch in the Bay. Shiner surfperch have not been sampled for PCB analysis in the Crescent. They have been observed to occur, however, at a depth of 2 - 4 m in waters to the west, and would likely be present in the subtidal portion of the Crescent (R. Fairey, pers. comm.). Small numbers of shiner surfperch were also collected by beach seine in spring and summer 2004 near the radio tower by the Bay Bridge toll plaza as part of monitoring related to the Oakland Harbor Navigation Improvement Project (Andy Jahn, personal communication). Shiner surfperch therefore do appear to be a key species in the local food web from a PCB cycling perspective. Shiner surfperch consume mainly small benthic and epibenthic crustaceans, sometimes adding in, or even switching to, major portions of polychaetes and clams (Jahn 2008). Like silverside and topsmelt, shiner surfperch have been shown to be excellent spatial indicators, showing patterns that match patterns in sediment contamination.

This simple, PCB-oriented depiction of the Crescent food web (Figure 5-1) provides a basis for considering key characteristics of potential indicator species for bioaccumulation. Each species provides a different integration of PCB concentrations in the food web, in abiotic compartments of the ecosystem, spatially, and temporally.

- Species at higher trophic levels integrate contamination at the lower levels. For example, Mississippi silverside provide an integrated indication of concentrations in the various epibenthic invertebrates that they consume. Forster's terns provide an even higher level of integration.
- Feeding strategies determine linkage to abiotic compartments. This is an important consideration for benthic species, which have feeding strategies that include filter-feeding, surface deposit-feeding, and subsurface deposit-feeding (Luthy et al. 2011). Filter- and surface deposit-feeders have a stronger linkage to recently exported particles from the watershed, while subsurface deposit-feeders are exposed to more of a mixture of particles exported from the watershed over the course of many years.
- Movement patterns determine spatial integration. Benthos are relatively stationary, and therefore indicate contamination at very small spatial scales. Prey fish move around the PMU (and in the case of topsmelt, probably beyond the PMU) and therefore integrate at a scale approaching or exceeding the area of the PMU. Piscivorous species generally move widely throughout the Bay, integrating at a regional scale.
- Lifespans and kinetics of uptake and elimination determine temporal integration. PCB concentrations in muscle tissue of long-lived species like striped bass probably represent multiple years of exposure and integration. Young-of-year prey fish sampled at the end of the summer represent exposure and integration over less than a year.

The sections below evaluate potential bioaccumulation indicator species in the Crescent according to these key characteristics.

b. Evaluation of Potential Indicators

Mississippi Silverside

General Characteristics

Mississippi silverside (*Menidia audens*) has high potential as a primary biosentinel species for monitoring changes in beneficial use impacts in response to reduced tributary inputs in the Emeryville Crescent PMU and in other PMUs where it is present. Over the last 20 years, *M. audens* has been established as an important indicator of wildlife exposure to PCBs in the Bay and mercury throughout the Bay-Delta Estuary, and much has been learned about its attributes as a biosentinel species (Jahn 2008, Slotton 2008, Greenfield and Jahn 2010, Greenfield and Allen 2013, Greenfield et al. 2013a,b). This species was collected at many locations throughout the Bay as part of RMP prey fish monitoring, although least commonly in Central Bay (Figure 5-2).

M. audens, along with topsmelt (*Atherinops affinis*, discussed below), is a member of the New World silverside family Atherinopsidae. *M. audens* is an invasive species that was introduced into Clear Lake and Bay Area lakes in the late 1960s, and has since spread widely across the Estuary and its watershed (Moyle 2002). *M. audens* is abundant in many shallow-water areas of the Estuary (Moyle 2002, Mahardja et al. 2016) and a major component of the Estuary food web, representing an important prey species for piscivorous fish and birds. *M. audens* is a pelagic species with an affinity for shallow water, generally occurring in areas that are at least seasonally freshwater (Greenfield and Jahn 2010). *M.* audens is considered primarily a freshwater species, and is widely distributed in freshwater habitats across California and the US (Moyle 2002, Neilson 2016). The diet of *M. audens* is generally considered to consist of zooplankton (copepods and cladocerans), insects, and small, pelagic invertebrates. Several studies have found *M. audens* to be a water-column forager to some degree (Elston and Bachen 1976, Li and Moyle 1975, Wurtsbaugh and Li 1985). However, some of these same studies also found, at times, a predominance of emerging dipterans (especially midge pupae) in the stomachs, which is consistent with the reason that this species was introduced in California: to control a nuisance midge by consuming its benthic stages. Pflieger (1975) stated that the feeding habits of *M. audens* are similar to, but less surface-oriented than, those of the brook silverside (*Labidesthes sicculus*), which eat insects in shallow water. Gut content studies on the Bay margins, however, have observed diets dominated by epibenthic invertebrates (Cohen and Bollens 2008, Greenfield and Jahn 2010). Overall, *M. audens* appears to be an opportunist, such that the habitat may influence its choices. The opportunism of *M. audens* has probably been important in its success in invading a wide variety of habitats (Cohen and Bollens 2008). *M. audens* grow to a size of 80-100 mm in their first year, and most die after spawning in their first or second summer (Moyle 2002). The fish typically collected in monitoring efforts (40-80 mm) therefore represent a contaminant exposure period of less than one year.

Advantages as a Trend Indicator in the Emeryville Crescent PMU

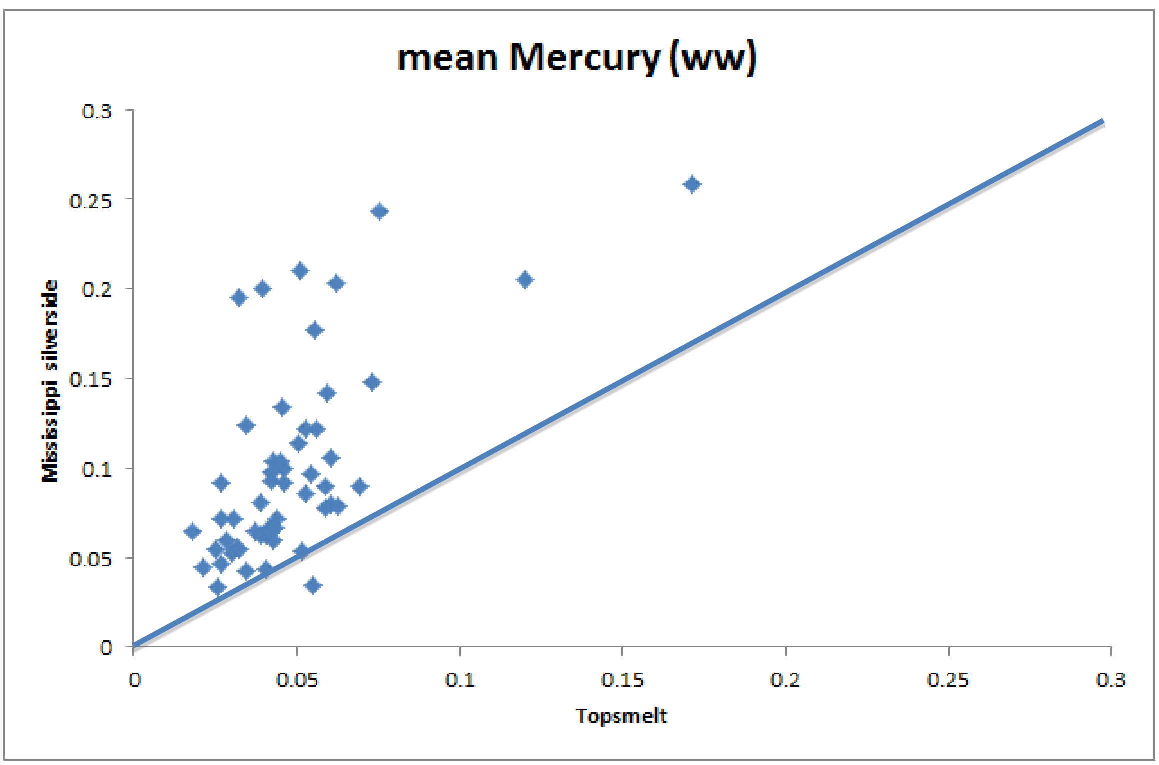
M. audens possesses many characteristics that make it well-suited to be a biosentinel for changes in biotic exposure to PCBs in response to reduced tributary inputs in the Emeryville Crescent PMU, and more broadly in other margin areas of the Bay.

- Linkage to beneficial use impairment (relevance to decision-making): Prey fish are abundant in the Bay and a major component of the Bay food web. They are important components of the diets of many Bay fish and wildlife species, and therefore have a significant role in the trophic transfer of bioaccumulative contaminants. The PCB TMDL does not include a target for prey fish. Concentrations in shiner surfperch are a direct measure of impairment in the TMDL, but this species is only potentially present in the subtidal portion of the PMU, relatively removed from the watershed input signal. However, prey fish are a good proxy for shiner surfperch because of substantial overlap in the invertebrate species they consume and the established linkage between PCBs in prey fish and PCBs in sediment on the Bay margins. In addition, PCB concentrations in prey fish provide an index of exposure of piscivorous wildlife that can be compared to published risk thresholds (e.g., Greenfield and Allen [2013]).

- Strength of contamination signal: The PCB contamination signal in *M. audens* is very strong. Average concentrations of the sum of 40 congeners in the 2010 sampling were 354 ppb ww for targeted sites, and 75 ppb ww for probabilistic sites (many of which were in un-industrialized portions of the Bay). A maximum concentration of 970 ppb ww was measured in Stege Marsh. These concentrations are generally higher than the concentrations that have been measured in shiner surfperch, the most contaminated sport fish species. The strong contamination signal enhances possibilities for detecting variation in congener profiles, which can be helpful in source identification.

- Site fidelity: In general, the mobility of fish can be a significant drawback in using them as local-scale biosentinels because they often forage over a wider range than the area of interest. A general advantage of small prey fish relative to larger predator fish species is that they have smaller home ranges (Minns 1995). *M. audens*, however, has an unusually narrow home-range that makes it an excellent biosentinel for monitoring food web contamination at the mouths of creeks where freshwater enters the Bay. Although it is tolerant of higher salinity, *M. audens* has an affinity for freshwater that limits its home range in the Bay. As discussed by Greenfield and Jahn (2010), available distribution information indicates that *M. audens* forages within specific marshes, creeks, or other inshore areas. *M. audens* is almost never collected in offshore portions of San Francisco Bay or in marine salinities (Orsi 1999), but does occur within Bay margins and upstream tributaries (Leidy 2007). In contrast, topsmelt (*Atherinops affinis*), which is also abundant on the Bay margins and was the other primary species targeted in RMP prey fish sampling, become relatively unavailable to beach seines when the tide is below 2 ft MLLW, which suggests migration to deeper water (Andy Jahn, personal communication). The greater affinity of *M. audens* for marshes and tributaries may explain their elevated mercury concentrations relative to *A. affinis*. In RMP prey fish monitoring, these two species were collected at the same location and time on many occasions, and *A. affinis* had the higher mean mercury concentration in only one of these paired samples (Figure 5-6). One of these cases where the two species were collected at the same location was at the "Ettie" station where flows from the Ettie Street Pump Station Watershed enter the Crescent. At this location the mean concentration in *M. audens* in four composite samples was 0.51 ppm dw (individual values of 0.39, 0.60, 0.64, and 0.42 ppm), while the mean for *A. affinis* was 0.15 ppm dw (individual values of 0.16, 0.14, 0.15, and 0.15 ppm). Given their affinity for freshwater, it appears likely that *M. audens* in the Crescent would have high site-fidelity for the two major freshwater entry points at the Ettie Street Pump Station/Emeryville Crescent North input and at the mouth of Temescal Creek, and not move into the subtidal zone. Whether *M. audens* moves between these two points, which are only 0.4 km apart, could be evaluated through tagging studies.

Figure 5-6. Mercury concentrations at locations where silverside and topsmelt were collected simultaneously. Line shows 1:1 slope.



- Temporal response: *M. audens* individuals that are present on the Bay margins are primarily less than one year old. They therefore provide an independent measure of variation in contamination from one year to the next, a desirable attribute in the measurement of interannual trends. This is in contrast to longer-lived biosentinels that may integrate exposure to persistent contaminants over a longer time-span.

- Potential as a leading indicator: As mentioned above, gut content studies on the Bay margins have observed diets dominated by epibenthic invertebrates (Cohen and Bollens 2008, Greenfield and Jahn 2010). Gut content analysis of *M. audens* collected from three margin sites in the Bay (n=10 from each site) found that the species mainly consumed epibenthic crustaceans (specifically, corophiid amphipods), with relatively lower abundance of insects and planktonic crustaceans (Table 5-1) (Jahn 2008, Greenfield and Jahn 2010). Another study of Mississippi silversides in China Camp marsh (North Bay) also found the species to primarily consume benthic species, and less utilization of zooplankton and insects (Visintainer et al. 2006). The epibenthic invertebrates that were dominant in *M. audens* diet in Greenfield and Jahn (2010), were either surface deposit-feeders (harpacticoid copepods and the cumacean *Nipoleucon hinumensis*) or filter- and surface deposit-feeders (*Corophium heteroceratum*), based on a summary of functional ecology of Bay benthos presented in Luthy et al. (2011). Luthy et al. (2011) also reported data on benthic community composition at several Central Bay sites, including a site off of Emeryville to the north of the Crescent. Other epibenthic invertebrates species that they found in moderate or greater abundance and were also mentioned by Greenfield and Jahn (2010) included *Leptochelia* (another surface deposit-feeder) and *Ampelisca abdita* (a filter-feeder). It thus appears that *M. audens* in the Crescent would be likely to consume primarily small epibenthic invertebrates that are exposed to PCBs via surface sediment or suspended sediment, making this species a potential leading indicator of changes in PCB concentrations on particles that are exported from the PMU watersheds.

- Ease of collection: Prey fish can be collected relatively easily and inexpensively from the shore via beach seines. No boat is required.

Table 5-1. From Greenfield and Jahn (2010). Length ranges and averages of the two species were similar: (topsmelt 28 to 101mm TL, mean=58 mm, N=30; Mississippi silverside 33 to 83 mm, mean=53 mm, N=30).

Dietary summary of two fish species.

Food category	Topsmelt		Mississippi silverside	
	Avg. %	Wtd. Avg. %	Avg. %	Wtd. Avg. %
Diatom	0.1	0.2	1.6	7.8
Microplanktivores[a]	3.7	5.7	0.7	0.4
Copepods and ostracods[b]	34.2	9.3	27.9	18.4
Large Zooplankton[c]	4.9	4.8	6.4	4.0
Small crustacean[d]	15.9	7.6	18.4	8.0
Large crustacean[e]	30.4	55.7	32.7	52.5
Insect[f]	4.0	6.5	11.5	8.4
Polychaete	5.8	9.0	0.3	0.4
Bivalve	0.2	0.0	0.0	0.0
Unidentified animal	0.8	1.0	0.4	0.2

[a] Foraminiferan, tintinnid, hydroid, or rotifera.
[b] Planktonic and epibenthic crustaceans < 1 mm body length (BL); mainly Harpacticoid copepods.
[c] Planktonic crustaceans >1 mm BL (calanoid copepods, Cyprid larva, *Neomysis* spp., and larval *Crangon* spp.).
[d] Cumaceans (*Nipoleucon hinumensis*) and copepoda (*Coullana* sp.).
[e] Amphipoda (e.g., *Corophium heteroceratum*), Tanaidacea (e.g., *Pancolus californiensis*), and Isopoda (e.g., *Synidotea harfordi*).
[f] Hemiptera, Diptera, and Coleoptera.

Disadvantages as a Trend Indicator in the Emeryville Crescent PMU

- Lack of certainty about presence in the Crescent: *M. audens* was successfully sampled at the "Ettie" station in the Crescent in 2009. Although it is expected that this species has persisted (through annual repopulation from larvae settling out of the plankton) at this location, and will persist into the future, it is not a certainty.

- Limitations and information gaps on spatial integration: *M. audens* appears likely to be a valuable indicator of contamination in the Crescent, centered at the location where the inputs from the West Oakland Watershed enter the Crescent and have their greatest influence. One information gap about this species as a biosentinel in the Crescent is the degree to which individuals move between the Ettie station and the mouth of Temescal Creek. If they are moving between these areas it will be more difficult to detect a distinct trend signal from the West Oakland Watershed.

- Linkage with the TMDL indicator species (shiner surfperch and white croaker): While the diet of *M. audens* overlaps significantly with the diets of shiner surfperch and white croaker (epibenthic invertebrates are a major dietary component for all three species), surfperch do not consume *M. audens* and croaker consume only small amounts of prey fish, so there is not a direct trophic linkage between these species. There is therefore some uncertainty as to how closely reductions in PCB concentrations in *M. audens* would be associated with reduced PCB concentrations in surfperch and croaker. However, based on the mechanistic understanding of PCB fate articulated in the TMDL food web model, it can reasonably be expected that the low sediment concentrations that drive down concentrations in *M. audens* would also drive down concentrations in surfperch and croaker.

Topsmelt

General Characteristics

A. affinis has potential value as a secondary biosentinel species for monitoring changes in beneficial use impacts in response to reduced tributary inputs in PMUs where *M. audens* is present, and as a primary biosentinel in PMUs where *M. audens* is not present. RMP prey fish monitoring has established this species as a valuable indicator of wildlife exposure to PCBs and mercury in the Bay. This species was collected at many locations throughout the Bay as part of RMP prey fish monitoring (Figure 5-3), and, in contrast to *M. audens*, was collected at a large number of stations in Central Bay.

As mentioned above, *A. affinis*, along with *M. audens*, is a member of the New World silverside family Atherinopsidae. In contrast to *M. audens*, *A. affinis* is native to the Bay and is primarily a saltwater species (Moyle 2002). *A. affinis* has a weaker connection than *M. audens* to zones of freshwater input on the Bay margins. *A. affinis* is found in coastal waters, bays, and estuaries from British Columbia to the Gulf of California. *A. affinis* prefers shallow bays, sloughs, and estuaries, and is one of the most common species found in the lower reaches of coastal streams and in upper estuaries, making it an important component of the diets of piscivorous fish and birds (e.g., Least Terns on Alameda Island [Elliott et al. 2007]). Most *A. affinis* in fresh or brackish water are young-of-year or yearlings. In the Bay, they are abundant in the shallows in March-September but move in to deeper water or the ocean in winter. *A. affinis* in general are bottom-grazing or algae-browsing omnivores. A study of gut contents on the Bay margins, however, observed a diet dominated by epibenthic invertebrates, very similar to the diet for silverside (Jahn 2008). The fish examined in Jahn (2008) were small. Larger topsmelt may consume a higher proportion of algae (Andy Jahn, personal communication).

Advantages as a Trend Indicator in the Emeryville Crescent PMU

Topsmelt possess several characteristics that makes it well-suited to be a biosentinel for changes in beneficial use impacts in response to reduced tributary inputs, but not quite as well-suited as Mississippi silverside.

- Linkage to beneficial use impairment (relevance to decision-making): Like silverside, topsmelt are a major component of the food web (e.g., Elliott et al. 2007) and provide a valuable index of exposure of piscivorous wildlife that can be compared to published risk thresholds (e.g., Greenfield and Allen [2013]).

- Strength of contamination signal: The PCB contamination signal in topsmelt is very strong, with average concentrations even higher than those for silverside. The higher averages are likely related to the greater proportion of topsmelt sites located in Central Bay. Average concentrations of the sum of 40 congeners in the

2010 sampling were 359 ppb ww for targeted sites, and 154 ppb ww for probabilistic sites. A maximum concentration of 1132 ppb ww was measured in Hunters Point South Basin.

- Site fidelity: The site fidelity of topsmelt appears to be strong enough to clearly distinguish variation among PMUs (based on the RMP PCB study), though not quite as optimal as the site fidelity for silverside. Available information suggests that topsmelt are likely to spend more of their time in subtidal waters, farther removed from the zone of maximum sediment PCB concentrations at the point of freshwater inputs in the PMU. As mentioned above, topsmelt is a saltwater species that appears to move into subtidal habitat when the tide is less than 2 ft above MLLW (Andy Jahn, personal communication), and that also moves into deeper water or to the ocean in winter. The consistently elevated mercury concentrations in silverside relative to topsmelt also suggest different habitat usage by these two species (Figure 5-6).

- Temporal response: Like Mississippi silverside, young-of-the-year topsmelt that are present on the Bay margins provide an independent measure of variation in contamination from one year to the next, a desirable attribute in the measurement of interannual trends.

- Potential as a leading indicator: Since the diet of young-of-the-year topsmelt appears to be very similar to the silverside diet, dominated by deposit-feeding and filter-feeding epibenthic invertebrates (Jahn 2008, Greenfield and Jahn 2010), topsmelt has similar potential as a leading indicator of changing concentrations in the PMU. One slight difference is that topsmelt are likely doing more foraging in subtidal waters away from the zone of maximum tributary influence, so they would not be quite as good of a leading indicator as silverside.

- Ease of collection: Prey fish are can be collected relatively easily and inexpensively from the shore via beach seines. No boat is required.

Disadvantages as a Trend Indicator in the Emeryville Crescent PMU

- Lack of certainty about presence in the Crescent: Topsmelt were successfully sampled at the “Ettie” station in the Crescent in 2009. Although it is expected that this species has persisted at this location (through annual repopulation from larvae settling out of the plankton) at this location, and will persist into the future, it is not a certainty. Based on RMP prey fish sampling, topsmelt appear to be more widely distributed in the Central Bay than silverside, so topsmelt are far less likely to be absent from the Crescent than silverside.

- Limitations and information gaps on spatial integration: Past RMP prey fish sampling suggests that topsmelt are likely to be valuable indicators of contamination in the Crescent, though less closely linked to watershed inputs than silverside due to their greater use of subtidal habitat.

Other Indicators

Shiner Surfperch

As discussed above, shiner surfperch are the most relevant indicator species in the Bay for assessing impairment of beneficial uses. This species has also proven to be a very useful biosentinel for evaluating spatial patterns and interannual trends. Repeated rounds of sampling of shiner surfperch by the RMP have demonstrated site fidelity that is strong enough to allow detection of statistically significant variation among sites in spite of a design that typically includes just three replicate composites per site.

The major drawback of shiner surfperch as an indicator species in the Crescent is a weaker linkage to the influence of tributary inputs, due to both their preference for subtidal habitat and also a diet that can include subsurface deposit-feeding polychaetes. There is also uncertainty relating to whether this species can be found in the Crescent in sufficient abundance to obtain samples. Another disadvantage is the greater effort and cost associated with trawling, the collection method usually used in RMP sampling, to collect the fish. However, a large beach seine may be effective in collecting this species in the Crescent (Andy Jahn, personal communication).

Overall, the status of this species as a definitive indicator of impairment makes it a valuable indicator of the status of the PMU. However, it is more suited to a role that is supplemental to silverside, which is better suited as a leading indicator of response to reduced watershed inputs.

Benthos

Monitoring of contaminant trends in benthic species in the Bay has yielded valuable information on spatial patterns and long-term trends, and linkage to changes in pollutant loads. Resident clams, in particular, have been shown to be valuable indicators, most notably *Macoma balthica* on a mudflat near Palo Alto with a trace metal time series that began in 1975 and continues to the present (Hornberger et al. 2000), and *Corbula amurensis,* which has been monitored for selenium and other metals in the North Bay since 1995 (Stewart et al. 2013).

The advantages of using benthos to monitor PCBs in the Crescent would relate to potential as a leading indicator with a close linkage to tributary inputs. These advantages have been exemplified by the *Macoma* monitoring on the Palo Alto mudflat. The close linkage to tributary inputs is based both on the potential to collect clams and other benthos at locations in the zone near the freshwater inputs where particles deposit and the option to focus on organisms the feed on surface sediment. *Macoma* is an example of a surface deposit feeder (though also capable of filter-feeding). Experiments by Cho et al. (2009) on the effect of addition of activated carbon to sediment at Hunters Point provided evidence of *Macoma* feeding on newly deposited sediment, resulting in an unexpected absence of effect of the activated carbon 18 months after the treatment.

There are several disadvantages, however, of *Macoma* and other benthos, relative to prey fish, as PCB biosentinels in the Crescent. One potential problem with *Macoma* is that it may not be present in the Crescent. Luthy et al. (2011) conducted benthic surveys of several Central Bay locations as part of their evaluation of Hunters Point. Very few *Macoma* were observed at any of the stations, including a transect in the margin area north of the Crescent. Other general disadvantages of benthos for trend monitoring of PCBs in the Crescent include an indirect linkage to species used in impairment assessment, lower concentrations and a weaker contamination signal, and a lower degree of food web integration.

A preliminary survey of the benthic community in the Crescent would be valuable in assessing whether the prey fish biosentinels are likely to be consuming epibenthic invertebrates as expected, and in assessing the potential of benthic species as biosentinels for long-term PCB trend monitoring. However, if the prey fish are present as expected, they would be preferred over benthos for trend monitoring.

Biota Surrogates: Passive Sampling Devices

The use of passive sampling devices to monitor sediment contamination at contaminated sites is an active area of research (e.g., Adams et al. 2007). Luthy and coworkers explored the use of these devices to assess PCB dynamics at Hunters Point (Cho et al. 2009, Luthy et al. 2011). These devices can be deployed at locations of interest to measure accumulation of dissolved phase contaminants into an adsorbent medium, such as a film of polyethylene. A single film can be used to monitor dissolved concentration profiles with depth, extending from subsurface sediment into the water column. The potential advantages of these devices in a setting like the Crescent include the ability to place them at any location of interest (with vandalism the only concern), the acquisition of site-specific and compartment-specific data, time-integration over the period required for contaminants to reach equilibrium, and high value in assessing passive bioaccumulation from the dissolved phase by benthos (including from challenging matrices like sediment pore water).

Several limitations, however, make passive samplers less useful than prey fish or sediment as spatial and interannual trend indicators in the Crescent. Impairment is related to PCB exposure at higher levels in the food web, either in sport fish for humans or prey fish for piscivorous wildlife. Exposure at these higher trophic levels is a function of both the passive accumulation and dietary uptake through ingestion of particles by benthos, followed by dietary uptake by species that consume the benthos. The linkage of the dissolved phase to impairment is therefore less direct than that of tissue concentrations in fish or possibly even of concentrations in bulk sediment (which have been shown to correlate with concentrations in fish). The dissolved concentrations that are measured with passive samplers are also an indirect measure of the export from the watersheds, which is predominantly in the particulate phase. Finally, a disadvantage relative to prey fish is the lack of integration of the food web.

Passive samplers do, however, offer some advantages as indicators of PCBs in PMUs. A key advantage is as a means of obtaining a time-integrated estimate of PCBs in the dissolved phase in either the water column or in sediment pore water. This information is valuable input for modeling PCB bioaccumulation in indicator species in the food web (Gobas and Arnot 2010). Passive samplers allow for this information to be obtained in a more cost-effective manner than grab samples. Another advantage of passive samplers is that they can be deployed to measure concentration gradients across the sediment-water interface. Passive samplers provide an effective means of obtaining information on spatial and temporal gradients in dissolved PCBs, which can be valuable in situations where this pathway is of high importance. Overall, passive samplers have utility in addressing some of the PCB information needs in PMUs, and can provide a valuable complement to sampling of prey fish and bulk sediment.

c. Monitoring Recommendations

Based on the considerations discussed above, we make the following recommendations related to bioaccumulation monitoring in the Emeryville Crescent.

Preliminary Field Studies

- Prey fish survey - Prey fish have great promise as a cost-effective indicator of interannual trends in response to changes in tributary loadings. A relatively intensive initial survey should be conducted to sample them in the Crescent. Sampling locations should include both points of tributary inflow and other shoreline locations to assess movement. PCBs should be analyzed. Gut contents should be analyzed to provide empirical information on prey selection (and linkage to surface or subsurface sediment compartments).
- Shiner surfperch - Shiner surfperch should be collected from the subtidal portion of the Crescent. PCBs and gut contents should be analyzed.
- Benthos - The composition of the benthic community should be evaluated. This will provide information on the availability of fish prey and linkage to surface or subsurface sediment compartments. Benthic species could possibly also serve as biosentinels if the prey fish are not present.
- Surface sediment survey - A spatial mapping of PCB concentrations in surface sediment would be valuable in understanding biosentinel exposure. The sampling should measure concentrations in the top 0.5 cm ("surface" as defined by Luthy et al. [2011] - to evaluate exposure of surface deposit-feeders) and in the top 5 cm ("surface" as defined in RMP monitoring - for comparison to data

for the top 0.5 cm and to other RMP sediment data from the margins and the open Bay).

- PCBs in water - Data needed to incorporate prey fish into the PCB food web model (Gobas and Arnot 2010) should be collected. Concentrations of dissolved PCBs in water are important model input data that allow quantification of routes of exposure for fish.

Long-term Monitoring

- Prey fish - Annual monitoring of silverside at the creek mouths would appear to be an excellent indicator of interannual trends in response to changes in tributary loadings. After an initial period (perhaps 5 - 10 years) that characterizes interannual variation and the presence or absence of trend, a power analysis could be conducted to determine whether a reduced frequency would optimize use of monitoring resources.
- Shiner surfperch - After an initial survey, shiner surfperch could perhaps be done on a five-year cycle as part of RMP sport fish monitoring. More frequent monitoring could be possible, if initial data suggest it would be valuable, in coordination with shiner surfperch monitoring at the other PMUs.

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6. Answers to the Management Questions

a. Can we expect a decline in any compartment of the PMU in response to projected load reductions in the PMU watershed?

A simple, one-box fate model suggests that a 15 cm mixed sediment layer could respond fairly quickly to significant changes in tributary inputs, with a change to a mixed layer concentration approaching a long-term steady state (and a new mass balance of inputs and losses) in 10 years. However, this rate of change to steady state is likely somewhat accelerated by the one-box assumption, and highly dependent on assumptions and estimates made for the input parameters. Nonetheless, the simple fate model is useful for illustrating the interactions among the numerous environmental processes affecting PCB fate and the likely net direction and relative rate of change under different scenarios.

These predicted changes in the mixed layer concentration would lead to similar changes in PCB exposure broadly across the entire food web. A significant amount of food web transfer of PCBs to species of interest occurs through benthos that are surface deposit feeders and filter feeders that can be expected to respond relatively quickly to reductions in ambient surface concentrations, which may in turn respond relatively quickly to reductions in tributary inputs.

b. How should tributary loads be managed to maximize PMU recovery?

The ESPS Watershed accounts for a minimum estimated 41% of the tributary export of PCBs into the Crescent. The load estimate for the Temescal Creek watershed also accounts for 41%, and 18% is estimated to come from the Emeryville Crescent North watershed. However, per unit area of each watershed, ESPS Watershed has the highest yield (19 g/km^2), followed by the Emeryville Crescent North Watershed (10 g/km^2) and the Temescal Creek Watershed (8.3 g/km^2). Recovery of the Crescent from PCB contamination would be maximized by pursuing a load reduction strategy that encompasses any remaining older industrial areas in all three of these watersheds. However, given the greater density of sources and source areas indicated by the yields, the most cost-effective phased strategy would be to focus earlier efforts in the ESPS Watershed.

The vast majority of the tributary loads that are retained within the Crescent are likely delivered by storms with magnitudes less than the 1:1 year return interval. More flow is delivered by these smaller storms, and more of the input is likely to be retained. From a PMU perspective, it appears that managing and monitoring these smaller storms is more important than managing and monitoring loads from larger storms. However, given the uncertainty in the temporal distribution of the loads, further data collection would be needed to verify that this conclusion is not an artifact of limited data and the assumption that rainfall distribution is a good surrogate for temporal load distribution.

c. How should we monitor to detect the expected reduction?

Preliminary field studies are needed to confirm the hypotheses put forward and information gaps identified in this conceptual model report. These include the following.

1. A survey of the presence, distribution, and PCB burdens of biota in the Crescent. Measurement of PCB concentrations in the two prey fish species is needed to establish a baseline. Sampling for shiner surfperch should also be attempted to determine the distribution of this species in the Crescent and evaluate PCB concentrations where it is present.
2. A survey of the spatial pattern of PCB concentrations in surface and subsurface sediment.
3. Other data (in addition to sediment concentrations) needed to quantify routes of exposure in prey fish, including data on prey fish diet (i.e., gut contents) and water column PCB concentrations. In other words, data needed to incorporate prey fish into the PCB food web model (Gobas and Arnot 2010) should be collected.
4. Data on PCB loads in stormwater from Emeryville Crescent North and Temescal Creek or data on concentrations sufficient to calibrate a model used to estimate loads.

Monitoring for tracking declines in PCB loads and impairment of the Crescent should include the following elements.

1. Annual monitoring of concentrations in prey fish. After an initial period that characterizes interannual variation and baseline concentrations, a power analysis could be conducted to determine the appropriate monitoring effort needed to observe a desired degree of change.
2. Periodic monitoring of concentrations in shiner surfperch as an ongoing measure of impairment. After an initial survey, this could perhaps be done on a five-year cycle as part of RMP sport fish monitoring.
3. Tributary concentration and possibly load monitoring that is consistent with the trend monitoring strategy under development by the Sources, Pathways, and Loadings Workgroup, ideally spatially and temporally linked to any ongoing fish and sediment monitoring in the Crescent.
4. Periodic (preferably annual) extreme near field receiving water sediment traps or surface sediment monitoring to approximately capture whole season net load concentrations. This in combination with annual prey fish monitoring would illustrate any lags or inertial responses between loading changes and total inventory or food web effects.